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A BIOMEDICAL PROGRAM

FOR

EXTENDED SPACE MISSIONS

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

PREPARED BY THE STAFF OF THE
DIRECTORATE OF MEDICAL RESEARCH AND OPERATIONS
WITH THE ASSISTANCE OF
BELLCOMM, INC.

APPROVED: Charles A. Berry M.D.
CHARLES A. BERRY, M. D.
DIRECTOR,
MEDICAL RESEARCH AND OPERATIONS

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INTRODUCTION

Man has unique abilities to receive and process information, to perceive and evaluate situations and to make and implement on-the-spot decisions. The presence of man on missions with exploratory and investigative objectives can, therefore, maximize the benefits accruing to mankind from the space effort. The rather significant record of accomplishments during the Mercury, Gemini and Apollo programs confirms this position.

Projecting into the future of manned space flight, all advanced concepts impose certain investigative requirements which are the same regardless of choice among program alternatives. These are:

a. to obtain greater knowledge on man's psychophysiological response to space flight;

b. to expand present understanding of design requirements for Man/Machine systems; and

c. to develop long duration flight systems and operations capability.

The preservation of man's well-being and ability to function effectively in space is the prime responsibility of the Directorate of Medical Research and Operations of NASA's Manned Spacecraft Center. Consistent with this responsibility the biomedical effort was directed primarily towards demonstrating that man can remain alive and operationally effective long enough to complete the planned lunar landing mission. It is important to note that Mercury, Gemini and Apollo were, and are, primarily engineering programs not intended to produce biomedical data of general predictive value for use in the design of advanced space systems. Flight qualification of the crews in these programs was accomplished by scheduling missions so that flight duration was extended according to a geometric progression. Starting from a suborbital flight of a few minutes in Mercury, flight duration was approximately doubled in each succeeding mission until a fourteen day exposure was achieved in Gemini. Both ground-based studies and in-flight observations from preceeding increments were used to build the confidence level required before extension in flight duration was certified as safe.

Unconditional qualification of man for extended space missions necessitates modifications in both the flight certification approach and the level of investigative efforts. Special emphasis must be placed on the physiological and behavioral processes that respond to stresses slowly with time and are likely to become important during prolonged space flight. Of particular interest are weight loss, cardiovascular function, bone and muscle metabolism, hematological changes, vestibular function, and long-term decrements in physical and behavioral performance. The program description which follows sets-forth current plans for accomplishing the task of space-rating man. Both known and potential problems are identified and, where possible, operational requirements are indicated. Investigative aims are also established.

The following individuals, listed in alphabetical order, have contributed to the preparation of this document: Drs. G. G. Armstrong, C. M. Barnes, E. L. Beckman, L. E. Bell, C. A. Berry, R. A. Boster, A. D. Catterson, D. O. Coons, M. R. De Lucchi, L. F. Dietlein, J. K. Ferguson, C. L. Fischer, B. A. Gropper, E. S. Harris, W. R. Hawkins, D. B. Hoffman, W. E. Hull, C. A. Jernigan, R. L. Johnson, G. F. Kelly, W. W. Kemmerer, A. N. Kontaratos, L. R. Loper, R. E. McGaughy, J. L. McQueen, E. L. Michel, E. C. Moseley, L. D. Nelson, B. D. Newsom, G. J. Pesman, P. C. Rambaut, M. A. Robinson, J. A. Rummel, R. L. Sauer, W. H. Shumate, M. C. Smith, Jr., L. D. Sortland, R. E. Waite, J. M. Waligora, H. O. Wheeler, and N. Zill. Thanks are due to Miss U. L. Graf and Mrs. G. D. Necessary for typing and proofreading the document.

GENERAL CONCEPTS

INTERNAL ENVIRONMENT

The interstitial fluid, with which body cells are bathed, and the blood plasma, with which body cells carry out continuous biochemical exchanges, constitute collectively the internal environment of the human organism. One of the cardinal principles of present day physiology is that fluctuations in the physical properties and chemical composition of the internal environment must be confined to extremely narrow limits. Otherwise the well-being of body cells suffers leading to degradation of man's ability to perform mental and physical tasks.

The internal environment is regulated by means of highly complex compensatory mechanisms developed in man through evolution. These compensatory mechanisms operate to counteract and minimize fluctuations of the internal environment caused by external physical changes, by physical activity, by pathological states, or by emotional conditions.

RESPONSE TO STRESS

Stress in any physical, chemical, or emotional factor that affects the constancy of the internal environment. The physiological response to stress proceeds in two phases. First, nonspecific reactions are invoked almost instantly and are characterized by a release of stress hormones and by increases in pulse rate, respiration rate and blood pressure. These reactions are short lasting, possess a defensive value to the organism, and characterize the physiological accommodative* (self-adjusting) measures that assure viability of the organism.

Secondly, imposition of prolonged accommodative measures brings about additional alterations in systematic processes. The gradual alkalinization of the blood in subjects exposed to low oxygen tension (mountain climbing) illustrates this point. Acclimative* processes may be long-lasting, need not be pathologic, and are often operative at a level where detection is difficult. The time required to achieve the steady state (i.e., to complete the process of acclimatization) depends on the nature of both the imposed stress and the affected physiological systems, and ranges from hours or days to weeks or months.

It is well to draw attention to the fact that the compensatory mechanisms have a wide but not unlimited regulatory capability. If the imposed stress is too great or persists too long, these mechanisms will be over powered. Degradation of performance in vital functions may then ensue, at a rate depending upon the nature of the stress and the systems affected.

Readjustment to the pre-exposure physiological state is gradual and occurs slowly following the removal of the imposed stress. Any irreversible effect should be considered pathologic and should be regarded as permanent injury sustained by the exposed individual.

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*See Appendix 1 for explanation of term.

In summary, performance of vital functions during an exposure to stress can be affected early or late, can deteriorate slowly or rapidly and can be impaired reversibly or irreversibly.

REVIEW OF FLIGHT RESULTS

Environmental factors believed to affect performance to the many stress parameters are identified in Table 1. The least understood feature of spaceflight is, however, the null-gravity state, inasmuch as no ground experience is either available or can be acquired.

Prior to spaceflight untested but plausible theories have been proposed predicting catastrophic failures of various vital functions in an organism suddenly exposed and maintained in an environment lacking the stimulus of gravitational force. Orbital experience refuted these theories but by the end of the Mercury Program positive evidence was available to indicate that significant physiological responses were occurring.

Studies were conducted during the Gemini Program to evaluate the magnitude of the flight-related effects first noticed late in the Mercury Program. These studies confirmed that major physiological systems exhibit consistent and, in retrospect, predictable changes after exposure to space flight. They also demonstrated that all changes were completely reversible for flights lasting up to two weeks.

Medical results obtained from actual space flight situations are listed and briefly discussed in Table 2. The fact that acclimative responses were not observed in systems other than those indicated in the table could merely mean that although additional physiological changes occurred they were not of sufficient magnitude to be detected by the methods employed.

EXISTING UNCERTAINTIES

In considering flight observations, it is important to realize that the available data are insufficient to permit confident extrapolation to major extensions in mission duration. Still ahead is the task of determining the precise nature, the ultimate severity, and the fundamental etiology of all changes in man's functional capabilities during and following prolonged space flight. Three circumstances, however, make such determination difficult. First, basic knowledge on the "normal" or "reference" functional capabilities of the human organism is relatively limited despite rapid advances in medicine and physiology. For example, individuals of the same build, sex, age, and a dozen other similar characteristics (i.e., matched as well as possible) have different physiological responses to the same treatment. Additionally, the same individual may respond differently to an identical stress imposed at different times. Secondly, inflight stressors act collectively, affect more than one physiological system and are difficult to evaluate singly. Our present understanding is also inadequate to permit meaningful extrapolations from single to multiple stressors and from one specific composite situation to another. Thirdly, powerful compensatory mechanisms can mask physiological disturbances until conditions become critical.

Presently it is still not certain whether physiological changes attributable to space flight conditions reflect gradual adaptation rather than progressive deterioration of body functions; whether or not they are self-limiting as mission duration increases; and whether or not the employed clinical mensuration techniques are sufficiently sensitive to detect all occurring accommodative and acclimative processes.

It is also possible that physiological normalcy in space differs from that on Earth and that potentially significant deviations from acceptable terrestrial limits are required for successful acclimatization to space flight conditions. If this proves to be true then man's ability to tolerate re-entry and post-landing stresses could be impaired without the necessary occurrence of in-flight degradation.

TABLE I

THE EFFECTS OF ENVIRONMENTAL FACTORS ON PERFORMANCE PARAMETERS

		INHERENT												EXTRANEOUS																									
		INTRAVEHICULAR								EXTRAVEHICULAR				MECHANICAL				AMBIENT				PHYSIOLOGICAL				HUMAN ENGINEERING					MOTIVATIONAL EMOTIONAL				SOCIAL				
PERFORMANCE PARAMETERS	ENVIRONMENTAL FACTORS	WEIGHTLESSNESS	RELATIVE PHYSICAL RESTRICTION	ALTERED PERIODICITIES	REDUCED BAROMETRIC PRESSURE	ENRICHED OXYGEN ATMOSPHERE	DILUENT GAS (OTHER THAN N_2)	LACK OF DILUENT GAS	ARTIFICIAL GRAVITY	SUBGRAVITY STATE	LACK OF LIGHT DISPERSION MEDIUM	PRESENCE OF SPACE SUIT	NEED FOR TRANSIENT DECOMPRESSION	NOISE	VIBRATION	LINEAR ACCELERATION	ROTATION	OXYGEN STARVATION	CONTAMINANTS ACCUMULATION	LOW OR HIGH TEMPERATURE	LOW BAROMETRIC PRESSURE	INADEQUATE ACCOMMODATION TO O-G STATE	EXPOSURE TO RADIATION	DISEASE	INJURY	INEFFICIENT WORK-REST CYCLES	INADEQUATE TRAINING	LOW VOLUME PER MAN RATIO	INADEQUATE MAN/MACHINE INTERFACE	SENSORY OVERLOAD OR UNDERLOAD	LOSS OF ACCUSTOMED PATTERNS	LOW INTEREST IN WORK	HIGH COST (e.g., EXCESSIVE DISCOMFORT)	LOW REWARD EXPECTATION	LIMITED SOCIAL ROLES	INAPPROPRIATE CREW STRUCTURE	LACK OF CENTRAL AUTHORITY	LACK OF PRIVACY	LIMITED INTERPERSONAL INTERACTION
AFFERENT FUNCTION	VISION					P					P	P			X	X		X	X	X	X	X																	
AFFERENT FUNCTION	AUDITION													X				X	X	X	X	X																	
AFFERENT FUNCTION	SOMESTHESIS											P			X			X	X	X	X	X																	
AFFERENT FUNCTION	SMELL																																						
AFFERENT FUNCTION	TASTE																																						
EFFERENT FUNCTION	ORIENTATION	P							P								X		X	X	X	X	X	X															
EFFERENT FUNCTION	POSITION KEEPING	D																																					
EFFERENT FUNCTION	TRANSLATION	D							P	P							X																						
EFFERENT FUNCTION	PSYCHOMOTOR RESPONSE								P			P			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
EFFERENT FUNCTION	VERBAL COMMUNICATION						P							X	X	X																							
EFFERENT FUNCTION	WORK CAPACITY	D						P		P		D						X	X	X	X	X	X	X	X	X	X												
EFFERENT QUALITY	ACCURACY		P								P			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
EFFERENT QUALITY	SPEED		P								P	P		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

NOTES:

P = POSSIBLE INTERFERENCE OR DEGRADATION; D = DEFINITE INTERFERENCE OR DEGRADATION

X = INDICATES EFFECT WHOSE SEVERITY DEPENDS ON THE AMPLITUDE OF THE IMPOSED STRESS.

WHERE NO ENTRY IS INDICATED, THE EFFECT IS CONSIDERED TO BE RELATIVELY MINOR OR IRRELEVANT.

TABLE 2
STATUS ASSESSMENT OF MAJOR HUMAN SYSTEMS

AFFECTED SYSTEM	NATURE AND TIME OF OBSERVATION	PROBABLE PRIMARY CAUSE	DEPTH OF STUDY
MUSCULOSKELETAL	POSTLANDING 1. MINIMAL LOSS OF BONE DENSITY 2. MINIMAL LOSS OF MUSCLE TISSUE 3. REDUCED EXERCISE CAPACITY	WEIGHTLESSNESS AND RELATIVE INACTIVITY	MODERATE
ENDOCRINE	INFLIGHT (WELL INTO MISSION) APPARENT DEPRESSION OF STRESS HORMONES POSTLANDING ELEVATION OF STRESS HORMONES	? MECHANICAL STRESS DURING AND FOLLOWING REENTRY	MINIMAL
EYE, NOSE, THROAT, SKIN, BODY MASS	INFLIGHT 1. EYE IRITATION 2. NASAL STUFFINESS 3. THROAT HOARSENESS 4. SKIN DRYNESS, DANDRUFF 5. MODERATE LOSS OF BODY WEIGHT	OXYGEN ATMOSPHERE WEIGHTLESSNESS AND RELATIVE INACTIVITY	MODERATE
CARDIOVASCULAR	INFLIGHT INCREASED HEART RATE DURING LAUNCH, EVA, AND REENTRY POSTLANDING 1. SHORT LASTING INCREASED HEART RATE 2. REDUCED TOLERANCE TO CHANGES IN POSTURE 3. REDUCED EXERCISE CAPACITY	MECHANICAL STRESS, PSYCHIC STIMULATION WEIGHTLESSNESS AND RELATIVE INACTIVITY	EXTENSIVE
BLOOD	POSTLANDING 1. MODERATE LOSS OF BLOOD VOLUME 2. MINIMAL LOSS OF PLASMA VOLUME 3. DECREASED RED-CELL MASS 4. INCREASED WHITE-CELL COUNT	WEIGHTLESSNESS AND RELATIVE INACTIVITY OXYGEN ATMOSPHERE AND WEIGHTLESSNESS GENERAL STRESS	MINIMAL
CENTRAL NERVOUS	INFLIGHT 1. SLEEP PROBLEMS 2. MOTION SICKNESS (APOLLO 8 & 9)	DISRUPTION OF DIURNAL RHYTHMS, NON-SIMULTANEOUS SLEEPING OF CREW, POSITIVE EXCITEMENT, THREAT OF POTENTIAL DANGER AND UNFAMILIAR ENVIRONMENT (WEIGHTLESSNESS, CRAMPED QUARTERS, RESTRAINTS, ETC.) UNRESTRAINED IVA UNDER WEIGHTLESSNESS	MINIMAL
RESPIRATORY	POSTFLIGHT SOME REDUCTION IN VITAL CAPACITY	SPACE CABIN ATMOSPHERE (PRESSURE AND COMPOSITION)	MINIMAL

APPENDIX 1

EXPLANATION OF TERMS

The terms accomodation, acclimatization, and adaptation as used in this document refer to adjustments in the physiological status of the body. The nature and distinguishing characteristics of these adjustments are explained in the following paragraphs.

Accomodation

Accomodation is the result of processes leading to adjustments or reconciliations within an organism that has acquired through evolutionary changes the capability of maintaining a constancy of internal environment despite changes in the external environment. The resultant effects may be short or long lasting, but are never influential in altering the genetic structure of progeny.

An example of the process of accomodation is the redistribution of blood volume in the human organism, particularly in the venous system, when the effect of gravity is absent and fluids are free to flow according to the relevant functional and anatomical parameters, such as venous system volume capacity, regional compliance, neuromuscular effects, etc. Accomodation to a changing environment does not imply the invocation of new functional capability and can take place only within the range of limits prescribed by characteristics of individual systems. Not all accommodations need be pathological; many are merely conservational.

Acclimatization

Acclimatization is the process of becoming "accustomed" to a new or different environment. Becoming "accustomed" implies that the organism has been able to utilize the flexibility of existing physical-chemical capabilities to overcome adverse environmental influences and retain a relative constancy of internal environment, necessary for viability of the cellular components of the organ systems. One sees an example of acclimatization in mountain climbers who first react to the hypoxia-producing environment by accomodating, breathing faster and deeper as the lower oxygen tension in the blood drives the medullary respiratory centers to increase the respiratory effort and thus bring more air to the lungs. Acclimatization may ensue if the period of exposure is sufficiently long and stressful, whereby the hematopoietic system is driven to produce additional red cells which appear in the arterial blood, creating additional oxygen carrying capacity. As the oxygen carrying capacity of the blood is increased, the processes of accomodation may subside or disappear as the individual becomes able to survive in the new environment. All this occurs because certain responsive physiological subsystems have reacted sufficiently to overcome the adverse effects. Acclimatization persists only so long as the stressing factors persist. Readjustment to equilibria more characteristic to the "normal internal environment" follows termination of exposure to the stressful environment.

Adaptation

During the billions of years past, the earth has been changing and is changing now. Animal life started as a very primitive form, and too, has changed with the changing terrestrial, aquatic and atmospheric environments. The selective incorporation of favorable structural and functional features arising from random variations in design makes possible the generation of progeny more suited to the current environment. This is the essence of organic evolution and the term adaptation may be thought of as the concert of processes which increase the suitability of the individual to survive in an otherwise hostile environment. Such changes in bodily structure and function, having been incorporated in the genetic coding structure of each cell, may be transmitted to successive progeny. As for man's participation in space travel, it is not strictly correct to refer to him as adapting, for the reasons that the length of time required to accomplish genetic changes is unknown but certainly spans many generations. In space flight, only processes of physiological and psychological accommodation and acclimatization are operative.

OVERALL POSITIONS AND OBJECTIVES

GOAL

The primary goal of the biomedical program is the qualification of man for extended space missions. Basic to this goal is the requirement to demonstrate that man is able to:

1. Acclimatize to the space flight environment without physiological and performance decrements (crew protective measures may be required to prevent the development of possible degrading conditions);
2. Withstand re-entry stresses without injurious effects; and
3. Re-acclimatize successfully to normal Earth conditions.

MEDICAL POSITIONS

1. Satisfactory response during a 6-month exposure to the space flight environment will be sufficient to indicate that man can tolerate this environment for any length of time.
2. At least one crew consisting of no fewer than three astronauts must have flown a 6-month mission successfully before spaceflight can be certified as safe for other crews with duration of mission being no longer a constraint.
3. If even one crewman encounters medical problems referable to his flight exposure, the causes of the

observed symptoms must be delineated and countermeasures established prior to attempting longer manned missions.

4. Application of countermeasures before a definite need is demonstrated can disrupt the normal course of acclimatization to the space flight environment and can impede scientific interpretation of the returned data.
5. Medical observations are required continuously from the beginning of man-rating flights in order to identify and interpret correctly subtle changes.
6. For missions of over 6-months duration, it should be mandatory that a physician-astronaut be a member of the crew.
7. Man-attended animal experiments shall be employed as appropriate for obtaining in-flight physiological-data for mission-rating man, provided that such data cannot reasonably be provided through human experimentation.

SPECIFIC INVESTIGATIONAL AIMS

Neurophysiology

1. To determine the effects of the space flight environment on sleep patterns.
2. To determine the change in susceptibility to motion sickness as a function of:
   a. Time aloft
   b. Freedom of movement within the spacecraft
   c. Rotation of the spacecraft.

3. To determine the effects of sustained loss of gravitational cues on sensory perception (the special senses, kinethesis, and other somatic senses) and on spatial orientation.

Pulmonary Function and Energy Metabolism

1. To determine the effects of sustained weightlessness on the mechanics of breathing in which, normally, the gravitational forces interact with the respiratory muscles and elastic forces of the chest and lungs.
2. To determine the energy cost (metabolic gas exchange) at rest and during activity within the space cabin in suited and unsuited modes during normal flight during EVA, and during operational activities on non-terrestrial bodies.
3. To determine the degree and duration of arterial hypoxia due to pulmonary ventilation/perfusion inequality during spacecraft launch and re-entry.
4. To determine the occurrence of any alterations in alveolar gas transfer and in the control of breathing under prolonged combined effects of weightlessness and a low pressure mixed gas and/or pure oxygen environment.

Cardiovascular Function

1. To determine how adequately cardiac output is maintained in prolonged space flight.
2. To determine the extent to which space flight affects normal arterial pressure controls.

3. To determine how venous compliance and central venous pressure and their adjusting mechanisms are influenced by prolonged space flight.
4. To determine how cardiac function is affected by long duration space flight.
5. To determine the factors of space flight which cause changes in circulating blood volume and its distribution. To determine at what point and under what conditions a new equilibrium is established.
6. To determine the time course of changes in overall circulatory function as determined by provocative testing (tilt table, LBNP).

Nutrition and Musculoskeletal Function

1. To determine the actual caloric requirements and the variables in caloric utilization under varying workloads and under varying configurations of space suit constraints in long duration space flight.
2. To determine the space flight factors or stress conditions which might change caloric, water, electrolyte, or mineral requirements. To determine the extent to which they change these requirements.
3. To determine the predictive or mathematic factors by which energy costs of activity in space are different from those in the 1g environment.
4. To determine the extent to which glucose metabolism may be altered by space flight conditions (as noted in prolonged bedrest).

5. To determine whether variations in body mass during space flight are within the limits to be expected, assuming adequate food and water intake and work schedules comparable to those observed in Earth environment.
6. To determine the time-course and degree of skeletal and muscular changes due to the weightless flight. To assess the relative influences of weightlessness, relative inactivity, and the gaseous atmospheric environment.
7. To determine the best preventive and/or remedial measures to counteract bone and muscle deterioration coincident with space flight.
8. To determine the effects of long duration weightless flight on water and electrolyte balance.

Endocrinology

1. To determine the extent to which weightlessness *per se* will bring about losses of fluid in view of the known changes in body water distribution and balance secondary to changes in body position. To assess how anti-diuretic hormone is involved in the mechanism of this change during prolonged weightlessness.
2. To determine the extent to which changes in the metabolic cost of activity in space will be reflected by changes in thyroid hormone production, and the extent to which a cause and effect relationship can be established.

3. To determine the extent to which the predicted losses of minerals in long-duration space flight associated with increased bone resorption are mediated by elevated parathyroid hormone secretion.

4. To determine the extent and time-course of changes in adrenal cortical activity during prolonged space flight as both a reflection and mediating factor of stress response.

Hematology and Immunology

1. To determine the environmental factors responsible for the loss of red cell mass noted during Gemini. To determine the relative roles of:

   a. The 100% oxygen environment.

   b. Nitrogen in small amounts.

   c. Weightlessness.

   d. Duration of exposure.

   e. Diminished red cell production vs. increased destruction.

   f. Ambient total pressure.

   g. Vibration.

   h. Ambient temperature.

   i. Dietary factors.

2. To determine the space flight factors responsible for changes in plasma volume.

3. To determine the influence of long-duration space flight on the coagulation process, platelet function, and vascular friability. To assess the environmental factors responsible for such changes.
4. To determine and evaluate any alterations in inflammatory response which may occur as a result of long-duration space flight.
5. To determine the extent to which space flight may influence mitosis (cell division) and/or chromosomal composition. To determine which environmental factors are responsible and what preventive action can be taken if such changes do occur.

Microbiology

1. To determine the changes which may be expected in the microbial flora of flight crews during space flight.
2. To determine the influence of space flight conditions on the relative dominance of pathogenic microorganisms.
3. To determine whether and to what extent genetic alteration in microbiological organisms can be expected to occur as a result of the space flight environment. To ascertain whether a pattern of such changes can be anticipated.

Behavioral Effects

1. To determine whether and to what extent perceptual efficiency will be affected by long-duration space flight conditions.

2. To determine the changes in time and/or pattern of activity which will make performance of tasks in space most efficient and most comfortable for the astronaut.
3. To determine what changes in the tolerance limits to stress occur over time in extended periods of weightlessness.
4. To determine optimal inflight and EVA work-rest periods based on factors of (a) fatigue, (b) energy cost, (c) discomfort, and other stress indices.

PROGRAM VALUE

Since many of the observed effects on man attributable to space flight exposure were not predicted beforehand with any great degree of accuracy, it follows that the results of any biological investigations in this novel environment will contribute significantly to our understanding of basic physiology and behavior. This can only lead to advances in conventional medical practice, benefits to public health, and in the design and development of improved aerospace systems.

WEIGHTLESSNESS - BONE AND MUSCLE

STATEMENT OF PROBLEM

It has long been known that chronic confinement and inactivity result in metabolic alterations, including loss of nitrogen, calcium and phosphorus from muscular and skeletal structures. If these losses are significant or persist for a sufficiently lengthy period the possibility arises of developing osteoporosis, urinary calculi and diminished muscle mass, strength and motor performance.

Despite long-standing awareness of the above processes in cases of debilitating disease it is only recently that evidence has accumulated for their occurrence in normal individuals subjected to bed rest for two or three weeks. In these studies, modification of the direction of gravitational force may contribute to the observed losses. It is therefore apparent that prolonged exposure of the astronaut to both diminished activity and weightlessness might produce deleterious changes in the physiological and biochemical integrity of bone and muscle. Such deterioration could not be tolerated indefinitely.

It is recognized that losses of this kind have occurred in weightless flight. The significance of these losses and the rates at which they take place in flight are still unknown. More positive data must be obtained before limitations are placed on the time any individual should remain in a weightless condition and before the need for further specific countermeasures is established.

PAST MEDICAL APPROACH

Since the beginning of manned spaceflight an adverse response of the musculoskeletal system to weightlessness has been predicted (Ref. 1). Therefore, there has been a continuing vigilance into the effects of spaceflight skeletal integrity. So far, this has been confined to attempts at determining with X-rays whether or not changes in bone density occur, and whether or not these changes are accompanied by alterations in urinary excretion of calcium, phosphorus, magnesium and nitrogen. The levels of sodium, potassium and chloride in the urine have also been measured in an attempt to provide data which might explain the mechanism of weight loss observed on all orbital flights.

Varying degrees of bone density decrease were observed during the Gemini flight series, and these decreases were unrelated to the mission duration. For example, although Gemini VII was the longest manned mission to date, the losses in bone density measured pre- and postflight on this crew were markedly less than those observed in the two previous flights of four to eight days duration (Ref. 2). It is believed that the vast improvement in the retention of bone mass by the Gemini VII astronauts may be attributed, at least in part, to the routine exercises these astronauts performed and to the fact that their food was fortified with calcium (Ref. 3, 4).

Analysis of urine and plasma were performed on samples obtained preflight and postflight on the 14 day Gemini VII and on the three day Gemini IX. In addition, urine samples obtained inflight during Gemini VII were also analyzed. No significant changes in calcium excretion were seen in the first seven days of spaceflight, but on the eighth day an increase in this parameter became apparent and persisted until the fourth day postflight (Ref. 5). Since dietary intake of calcium was somewhat lower during flight than during the pre- and postflight phases, and since fecal excretion of calcium remained relatively unchanged, the net balance of calcium was significantly negative for the inflight phase.

Urinary excretion of magnesium increased significantly during the second week of flight in a manner similar to that observed for calcium. Replacement of losses postflight resulted in a positive balance.

Urinary excretion of phosphate also increased significantly during spaceflight. There was a slight, but statistically insignificant, increase in negative nitrogen balance during the weightless period. Losses of calcium, magnesium, nitrogen and phosphate in sweat were negligible.

Urinary analysis has also revealed a loss of calcium in the crews of the Vostoks 3 and 4 (Ref. 6).

Since the crews of all these missions were small and since their responses to spaceflight demonstrated a high degree of variability, the data obtained must be considered with great caution. Definite conclusions must await the application of more refined techniques to a greater number of subjects for longer periods of time.

In addition to these observations obtained during actual conditions of spaceflight, weightlessness has also been simulated experimentally by complete recumbency and by prolonged continuous water immersion (Ref. 7, 8, 9, 10). In these situations, considerable information has been gathered on the muscular and skeletal responses to a reduction in gravity stress. It appears that in healthy young adults urinary calcium excretion increases two to threefold within five weeks after confinement and a negative nitrogen balance develops. Quantitative X-ray studies of the bones have confirmed the underlying demineralization.

Difficulties with current long-term recumbency studies seem to emphasize that there are practical limits to the length of time such studies can endure. At the same time these studies reveal that conditions of stability in calcium excretion tend to establish themselves two or three weeks after the commencement of relative inactivity (Ref. 11).

Work is presently underway to investigate the relationship between nutrient intake and calcium and magnesium metabolism. Preliminary data from these studies indicate that the level of protein in the diet influences the rate of calcium excretion. Bone density appears to be diminished at high levels of protein intake (Ref. 12). An effort is being initiated to investigate the feasibility of applying biochemical techniques to calcium management during space flight (Ref. 13).

PRESENT MEDICAL POSITION

Bone losses in orbital flight studies to date are by no means indicative of skeletal pathology and moreover the losses which do occur are rapidly replenished within a relatively short period of time postflight. In bed rest studies lasting four weeks, the total loss of calcium represents only about 0.5% of the total body calcium pool. If such a loss is generalized to all skeletal tissue during actual space flight, there would be no significant weakening of the bone structure. A change in bone mass of less than five percent distributed evenly throughout the skeleton is probably not serious physiologically.

However, it should be pointed out that the trabecular bones which bear weight have a particularly large surface area. There is therefore a possibility of preferential calcium loss from the legs, vertebrae and os calcis. Mack (Ref. 3) in fact has shown a loss in density from the os calcis which far exceeds that which would be predicted from calcium excretion data. Further inflight studies are needed to clarify this question inasmuch as continuous bone demineralization during prolonged space flight may result in bone fracture at re-entry.

The countermeasures to progressive mobilization of the bone mineral that are considered partially effective at present include programs of isometric and isotonic inflight exercises, calcium supplementation of the diet and compressional devices to simulate gravity.

FUTURE EFFORTS

Although none of the changes observed thus far are considered excessive they do at least require that inflight experimentation be performed to confirm the earlier observations and to indicate whether research be initiated into ameliorative methods for use during long duration flights.

Ground based simulation studies (e.g., bed rest with and without exercise) have in the past proved useful and will continue to be valuable as a means of acquiring control data on variables that are not unique to weightless flight. It is now essential, however, to obtain definitive data in the Earth orbital situation on the effect of weightlessness on musculoskeletal status.

Bone densitometric studies pre- and postflight should continue and a wider variety of anatomic sites should be examined. Techniques for measurements of bone density should be further refined and used inflight.

In order to describe adequately the time course of the effect of weightlessness on musculoskeletal status, inflight measurements should be obtained not only on bone density but also on mineral balance, muscle strength and body mass.

There should be a continuous evaluation of general metabolism and nutrition before, during, and after flight. As little variation as possible should be allowed in the type and quantity of nutrients consumed during these three periods.

Rigidly accurate procedures should be applied to the sampling of foods and the collection of excreta, sweat, and skin and hair flaking.

Stringent limitations to the kinds of metabolic data which may be derived from inflight experimentation, require that adequate information be obtained from simulation studies to enable correct interpretation of inflight data. Understanding of bone formation and resorption rates on the basis of urinary calcium excretion is at present very uncertain. Careful assessment must be made of the effect of stress and varying nutrient intakes on mineral excretory rates.

If inflight data continue to demonstrate the occurrence of significant bone depletion, ground-based studies should be pursued to investigate the extent to which manipulation of the diet may be expected to control unstable metabolic states. Hormonal studies should also be initiated both to provide information on the mechanism of bone demineralization and, in addition, to evaluate the feasibility of controlling mobilization by hormonal administration.

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WEIGHTLESSNESS - CARDIOVASCULAR FUNCTION

STATEMENT OF THE PROBLEM

The cardiovascular system basically consists of a fluid pump (the heart) and a network of fluid filled visco-elastic tubes (arteries and veins) through which blood is transported to all parts of the body. The heart rate and the size of the vessels are regulated by elaborate mechanical, neural and hormone control mechanisms which adjust the local blood flow according to needs and which ensure a steady supply of blood to the brain. During routine daily activities the force of gravity alters the distribution of blood in the cardiovascular system and, consequently, change the nature of blood flow regulation. Thus the function of this system is highly dependent upon the effects exerted by the earth's gravitational pull.

The effects of null or diminished gravitational forces which are experienced during space flight have not been fully elucidated by simulations on earth. However, flight observations coupled with analyses of the cardio-vascular system have indicated the following potential problem areas when the forces of gravity are altered:

Cardiac Contractility

Reduction in work performed by antigravity muscles reduces the nutritive and waste removal requirements imposed upon the circulatory (cardiovascular) system; hence, the heart experiences a more sedentary existance. One mechanism by which it can decrease its total output is to reduce the forcefulness of each individual contraction.

Vascular Responsiveness

Alterations in the responses of vascular smooth muscle which occur with decreased stimulation (horomonal, nervous, mechanical) with changes in the contractile properties of smooth muscle cells and with alterations in vessel geometry due to change in intravascular volume will result in qualitative and quantitative changes in the cardiovascular function. In particular the vascular neural reflexes which compensate for drainage of intravascular fluid away from the heart when a man assumes an upright position in a gravitational field become less effective. This situation called "orthostatic hypotension" can develop after a few days in a weightless state and upon return to earth could lead to fainting due to inadequate brain circulation.

Capillary Exchange

Alteration in the transcapillary pressure gradients or the properties of the capillary walls change the quantity and the composition of the fluid which moves from the intravascular into the extravascular spaces.

Alteration of the Viscoelastic Characteristics of Vessels

Changes in vascular distensibility, especially that of the capacitance vessels (located principally in the venous circulation), markedly alter the quantity of blood returned to the heart as well as the time dependent characteristics of venous blood return, and thence, alter the output of the heart.

Decreased Endocrine Activity

Depletion of vasoactive hormone stores (e.g., norepinepherine) or decreases in their rates of synthesis effectively limit or alter the ability of the vascular system to respond to stress when the need arises. Smooth muscle responses to given concentrations of vasoactive hormones may also assume different patterns as adaptation to a new environment occurs.

Decreased Vascularity

Both an enriched oxygen atmosphere and a decrease in oxygen demands of tissues associated with decreased work will reduce the oxygen transport requirements placed upon the cardiovascular system. The rate of oxygen diffusion through the tissue spaces to meet cellular oxygen needs will become lower. Thus, the diffusion paths can be lengthened without compromising these needs. Under these circumstances, tissues become less vascular through a relatively slow process of acclimatization.

Shifts of Intravascular Fluid Volumes

Volume receptors which respond to vessel or heart chamber wall stretch are stimulated by shifts of fluid within the vascular spaces when gravitational forces are removed or decreased. Through neuro-endrocrine pathways, a diuresis is initiated and the total water content of the body is reduced. This results in partial dehydration of body tissues and reduces the capacity to respond to stress.

Non Space Related Conditions

Consideration must also be given to debilitating cardiovascular diseases and to other earth environmental conditions not unique to weightlessness. The occurrences of these are not precluded by weightlessness; hence, long term comprehensive longitudinal studies on flight crews and improved prediction models are required to establish probability tables to assist medical support of long duration missions.

PAST MEDICAL APPROACH

Efforts to date have been directed along four major avenues:

1. Basic physiological studies of the cardiovascular system to define mechanisms and sites of action for the effects of simulated weightlessness as well as the time course for both adaptation and readaptation of various components of the system.
2. Studies of potential countermeasures which were suggested by prior knowledge of cardiovascular function or were suggested by the early results of the basic studies.

3. Preflight, inflight, and postflight observations and measurements of selected indicators of cardiovascular function.
4. Programs conducted to define, develop, and verify new measurement techniques, instrumentation, and indicators of cardiovascular function.

Basic Studies of Mechanisms and Countermeasures

Studies of weightless effects have been hampered by the inability to achieve true weightlessness in earth laboratories for sufficiently long times.

Parabolic flights have provided short periods (measured in seconds) of weightlessness. These periods are further complicated by the preceding and following increased acceleration forces. Recumbency and fluid (water and silicone oil) immersion studies have also been used for experimental models of weightlessness. A few inactivity studies involving chair rest have been performed. Studies have also been made of pathological cardiovascular states which could serve as models of advanced stages of the potential, subtle changes induced by weightlessness.

These simulations or analog weightless studies have produced useful information, but have suffered from difficulty in execution as well as inability to simulate in all respects the same forces (or lack thereof) as weightlessness. Of these, the recumbency (bed rest) studies seem to provide the most useful information.

Data have been gathered concerning fluid compartment changes and subsequent diuresis and relative dehydration, possible loss of vasoactive hormone activity or the response of vascular smooth muscle, possible changes in muscular vascularization, and to the determination of orthostatic provocation test characteristics and patterns. Many of these studies have also sought information about potential countermeasures, i.e., effects of occlusive limb cuffs, the effects of maintaining plasma volume (both by pharmacological and replacement techniques) and the effects of physical exercise.

Flight Related Studies and Observations

The initial effort in space flight requires assurance to a reasonable degree that man could survive orbital flight, could function during orbital flight, and would not likely be inflicted with significant, irreversible losses to his health as a result of orbital flight. Hence, indicators of cardiovascular function for real-time, inflight status evaluation ("how goes it" information) and provocative postflight evaluations were selected.

The inflight indicators were selected on the basis of maximum information obtainable with the minimum impact on either the spacecraft or the mission. The major criteria for maximum information were critically related to the real-time status and safety of the crew. The essential inflight variables were heart rate, ECG, blood pressure, and a modified phonocardiogram (indicative of the onset of ventricular contraction). Superficial information relevant to cardiovascular reserve was also obtained by the heart rate response to the work imposed by pulling on the "Bungee Exerciser".

Changes in orthostatic tendencies were indicated by means of pre- and postflight comparisons of heart rate, blood pressure, and leg volume responses to passive tilting to a 70° head up position. Comprehensive physical examination and exercise tolerance tests provided additional information on changes in cardiovascular function.

Technological Advances

Sensitive, precise methods of detecting and following subtle changes and trends require invasive instrumentation. Such techniques, even at best, alter the function of the system either by poor mechanical impedance match between the instrumentation system and the biological system or by psychic loading of the biological system (or conversely by the damping effects of drugs used to suppress the psychic response to intravascular invasion). Consequently, all noninvasive measurement systems and instrumentation (in particular those related to pressure measurements, vessel and tissue compliance and cardiac output) have been followed and pursued with vigor. Additionally, adaptation and variations of currently used ground-based evaluations, such as the Lower Body Negative Pressure (LBNP) test substitution for the tilt table test have been sought which could be utilized under the special environmental conditions of space missions. The returns from technological projects, if successful, are of a magnitude to make feasible initial investigations into the most speculative proposals.

PRESENT MEDICAL POSITION

The following positions are tentative and could be altered as current and future investigations reveal new knowledge.

1. No detrimental effects on the cardiovascular system which would significantly affect the health or performance during flight, during reentry or upon resumption of earth related activities are anticipated from exposures of 30 days duration of weightlessness during orbital or lunar flights. Positions relating to longer than 30 days duration must await knowledge gained from future flight observations.
2. The cardiovascular system appears to adapt readily and functionally to weightlessness.

3. Problems involving the cardiovascular system can develop during stressful situations, (including exposure to earth's or other planet's gravitational fields) and not to null gravity per se, or will be due to diseases or conditions not unique to weightlessness.
4. Development of space orientated instrumentation for the study of the cardiovascular system must be granted a high priority.

FUTURE EFFORTS

Investigations should continue to:

1. Develop facts to replace assumptions by conducting and sponsoring investigations into basic mechanisms of cardiovascular function which are influenced by gravity and by conducting and sponsoring applied research to assess the significance of these mechanisms.
2. Develop new evaluation techniques and instruments both for ground laboratory use and for inflight use. For example, the lower Body Negative Pressure device can be tested as a possible inflight analogue of the tilt table test.
3. Develop readaptive aids, countermeasures, and methods for return to earth or to limit the weightlessness adaptive processes.
4. Develop better predictive models and diagnostic techniques to select crews having the least likely probability of developing inflight cardiovascular problems.

WEIGHTLESSNESS - PSYCHOMOTOR PERFORMANCE

STATEMENT OF THE PROBLEM

Man's capabilities to perform effectively are significantly influenced by the type of gravitational environment in which he must function. Zero-gravity and sub-gravity conditions alter the integrative motor-sensory patterns involved in the performance of psychomotor tasks from those to which the human operator is accustomed on earth (a one-g environment).

Three basic factors contribute to hypo-gravic effects: (1) Reactive forces generated by task activities introduce dynamic instabilities, which require energy expenditure by the man to maintain his body position or restraints which he may use to gain mechanical advantage; (2) the sensory information normally available to the operator (vestibular or proprioceptive) may be lacking, or spurious cues may intrude; (3) many materials and objects behave differently under zero-g conditions, than they do at one-g, thus changing the tasks themselves. These factors collectively mean that man's performance capabilities must depend upon the efficient design of the man-systems interfaces in integrating appropriate countermeasures (such as restraints) for the man and the devices he uses. They also indicate the nature of the investigative and mission planning efforts required for such integration. Training and familiarization, for example, may significantly modify the individual operator's initial responses to the sensory-motor environments of space and enhance his abilities to develop and maintain new integrative patterns over long-duration missions.

Weightlessness therefore has both advantages and disadvantages with regard to task performance and space operations. The advantages basically reflect the freedom from the constraints on motion and orientation imposed by the gravitational field. The disadvantages, in turn, reflect the need to provide substitutes for the desirable control information and forces normally provided by gravity.*

Many possible effects of prolonged weightlessness on man's sensory and physiological makeup have been postulated and investigated by extrapolating known biomedical and environmental factors which influence human performance. Tasks covering a wide spectrum of mission-related functions, such as manual control, visual and verbal information processing, and personal maintenance, have been studied analytically, and tested in Earth simulations and in progressively more complex space flights. By these means the major effects have been anticipated or held within safe limits. However, it is not possible to simulate adequately on Earth prolonged zero-g conditions and the nature of the integrative mechanisms underlying complex psychomotor performance

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*See the section on Artificial Gravity for a more detailed discussion of the tradeoffs and problems.

are still inadequately defined. Much additional information, therefore,is still required to provide the bases for the design and support of long-duration missions which may involve interactions with which we have little or no operational experience.

PAST MEDICAL APPROACH

The scope of psychomotor tasks in space has increased as the volume available for intravehicular activities has increased from the Mercury and Gemini to the Apollo spacecraft. Problems of intravehicular orientation, stability, and gross body activities were minimal in the Mercury and Gemini programs since their configurations essentially confined the astronauts to their couches. Mercury did not involve any EVA, but Gemini EVA experience demonstrated the value of mobility aids, and especially restraints to permit effective task performance.*

Apollo permitted significant IVA mobility and freed the crewmen from their couches, enabling representative shirt-sleeve operations planned for future missions to be evaluated. IVA sequence camera films documented samples of these activities, but no other objective or quantitative psychomotor performance measures were obtained. Inflight TV permitted real-time observation of some crew activities. Evaluations of these sources, plus crew debriefings, have been valuable in providing insights

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*See the section on EVA.

into some aspects of intravehicular mobility patterns, body stabilization and propulsion points, and other time-and-motion features which cannot be adequately simulated by zero-g conditions in water-tanks or parabolic flight.

Psychomotor aspects have been qualitatively evaluated in connection with many forms of astronaut performance via crew comments in-flight and in postflight debriefings. No in-flight maintenance has been planned, but such contingencies as the water spillage in Apollo 7 have deomonstrated the crew's capabilities to integrate the available information effectively and cooperatively perform the complex psychomotor tasks involved in their solution under zero-g conditions. Accuracy in manual tracking of small visual targets in TV aiming was revealed to be dependent upon the provision of adequate sighting aids. Continual voice monitors in all missions have provided ground observers with real-time information on the crew's subjective evaluations of their own psychomotor responses. Subjective reports have also indicated problems associated with initial adaptation to intravehicular movement under weightless conditions. Individual differences in drug responses have occurred and will require reassessment of prophylactic and therapeutic measures involving their use.

Experiments have indicated the effects of weightlessness on body systems and investigated the crew's physiological responses to such synthetic tasks as the inflight exerciser.

Visual studies have indicated an apparent enhancement of visual acuity under zero-g conditions, but more work on the oculo-vestibular interaction under weightlessness is needed to adequately explain the causative mechanisms.

PRESENT MEDICAL POSITION

Man has demonstrated his ability to adapt to prolonged weightlessness and perform complex psychomotor tasks effectively for periods of up to 14 days. The multiple stressors of space flight in the weightless environment may produce reactions affecting his basic motor-sensoty capabilities, including his vision, voice, motor coordination, physiological and psychological performance, but these changes are not necessarily prolonged, maladaptive, or beyond the combined abilities of the individual crewman and the ground support medical teams to manage successfully. Repeated exposures of an individual crewman to the stresses of launch, flight, and re-entry do not indicate any synergistic effects in degrading the capabilities to re-adapt to space and Earth gravitational conditions, up to three exposures of more than a year apart. There is no presently available evidence to define adequately limits for these adaptive capabilities in terms of the number, duration, or spacing of such repeated exposures.

Design and testing techniques developed from industrial and military experience provide adequate bases for evaluating the short-term adequacy of the psychomotor aspects of man-systems interfaces for spacecraft and surface installations. However, these are not yet capable of adequately simulating or predicting the combined effects of weightlessness with the multiple environmental stresses of space flight. Analytical techniques for the design of space tasks, with regard to their psychomotor characteristics, are being developed but are still largely empirical. Therefore, simulation for purposes of systems design evaluation, and for purposes of determining individual performance proficiency, are essential to the validation of the psychomotor acceptability of these systems.* Although the time, force, and accuracy patterns of complex human performance are highly dependent upon specific situational factors, standards for the motion capabilities of space suits can be related to basic anthropometric characteristics, as shown in Table 1.

Design information is available for the preliminary evaluation of the effects of hypo-gravic conditions on many tasks. Psychomotor aspects and metabolic costs have been studied for suit donning and doffing, walking gaits under various lunar surface and lighting conditions, task sequencing for equipment deployment, and time and accuracy in control tasks. Comparisons of performance times for such operational

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*For a more extensive discussion of factors related to simulation and spacecraft design, see the sections on Simulation and Habitability Factors.

tasks under lunar gravity conditions have indicated increases of suited performance times over baseline shirt-sleeve conditions of over 100%. However, all present zero-g and 1/6-g simulations change the situational dynamics through supports or a water medium which offers significant resistance to motion. This alters the temporal integrative patterns involved in task performance, and situational time estimates must be considered only approximations.

Psychomotor performance capabilities are not solely dependent upon the adequate initial design of the component tasks and support equipment, but are highly related to the overall adequacy of integration of these within the mission time-line. The familiarization of the individual crewman with the equipment and procedures associated with each task permits him to develop the personal integrative patterns, or skills, which are in turn adapted to suited and zero-g environments. The resistance of these skills to degradation under long-duration space mission conditions can be expected to be related to the adequacy of the individual's preflight training for these tasks, the availability of in-flight facilities to maintain his general physical fitness, the provision of sensory variation and recreational outlets to prevent psychological degradations, and the availability of means to practice and review the skills prior to their actual use. These latter review aids can include checklists, and verbal or visual reminders which may not directly exercise the psychomotor skills used in the task performance. The best available experience to date does not indicate any operationally significant psychomotor degradations, but there is no adequate evidence to establish ultimate time limits for the retention of the psychomotor components of such skilled performances over long-duration missions.

FUTURE EFFORTS

Future efforts will be directed toward two major objectives: (1) The further development of supportive methods and devices to optimize the design of the man systems interfaces and maintain man's in-flight performance capabilities, and (2) the development of observational, measurement and diagnostic techniques which will be minimally intrusive and capable of assessing man's psychomotor performance in intravehicular and extravehicular task environments.

Contributory efforts towards these major goals should include:

a. Development of flight equipment which optimizes the sensory-motor feedback from the task environment to the operator and which provides him with equivalent operational capabilities in both intravehicular and extravehicular conditions. This technology will include suit improvements in comfort, vision, and personal maintenance features. Tools, controls and displays, personal restraints, stability aids, and mobility aids for extravehicular operations will be further developed for the long-term support of man in orbital, lunar surface, and planetary missions.

b. Development of observational methods which permit acquisition of objective measures of the time, motion, force, and accuracy patterns of man's performance in nonlaboratory contexts. These will include extensions and improvements of present direct real-time visual monitoring by earth-based and in-flight observers through fixed and portable TV sensors and onboard displays. Displays of synthetic images can be derived from telemetered data obtained via sensors located on the man and his interfaces. These data are potentially compatible with computerized real-time and post-flight analyses to evaluate man's psychomotor responses using restraints, tools, and other aids within work contexts.

c. Development of diagnostic methods by which onboard observers or ground teams can evaluate the real-time status of each crewman's psychomotor capabilities. These will establish objective criteria for decisions involving the corresponding safety of mission activities, modification of time-lines to permit indicated therapeutic measures in case of degradation, and crew exchange or mission abort, as indicated. These methods must include performance assessments of standardized psychomotor tasks and measures of the level of integration of those component capabilities within actual mission tasks, whenever possible.

d. Development of effective onboard countermeasures for psychomotor degradation in order to prevent such effects and maximize man's remaining operational potential in case they do occur. This will, in turn, impact both the crew selection and training requirements, and the design of the man-spacecraft interface to permit the required observations and operating modes.

e. Development of mathematical models relating the effectiveness of psychomotor performance in diagnostic test batteries under ground simulations and space flight conditions. These models will serve as predictive tools themselves and will enhance the predictive values available from one-g, one-sixth-g, and zero-g operational simulators. This will require development of sensitive test batteries and periodic testing of each crewman's performance characteristics during pre-flight training, in-flight, and post-flight, and will be coordinated with crew selection and training efforts.

TABLE I

MAXIMUM PERFORMANCE REQUIREMENTS FOR THE ELEMENTARY BODY MOVEMENTS INTRAVICULAR AND EXTRAVEHICULAR WEAR, VENTED OR AT 3.7 PSIA

MOVEMENTS	RANGE OF MOVEMENTS (In degrees)	MAXIMUM TORQUE REQUIRED
A. NECK MOBILITY		
Flexion (forward-backward)	120	0
Flexion (left-right)	30	0
Rotation (Abduction-Adduction)	140	0
B. SHOULDER MOBILITY		
Adduction	45	1 ft. lb_f
Abduction	125	1 ft. lb_f
Lateral - Medial	150	1 ft. lb_f
Flexion	170	1 ft. lb_f
Extension	50	1 ft. lb_f
Rotation (X-Z Plane) Down-up	135	1 ft. lb_f
Rotation (Y-Z Plane):		
Lateral Rotation	35	1 ft. lb_f
Medial Rotation	95	1 ft. lb_f
C. ELBOW MOBILITY		
Flexion - Extension	140	1 ft. lb_f
D. FOREARM MOBILITY		
Supination (Palms up)	90	.2 ft. lb_f
Pronation (Palms down)	75	.2 ft. lb_f
E. WRIST MOBILITY		
Palmar Flexion	75	.2 ft. lb_f
Dorsiflexion	65	.2 ft. lb_f
Abduction	50	.2 ft. lb_f
Adduction	30	.2 ft. lb_f
F. TRUNK - TORSO MOBILITY		
Trunk Rotation (abduction - adduction)	70	2 ft. lb_f
Torso Flexion (lateral - medial)	50	2 ft. lb_f
Torso Flexion (forward)	90	2 ft. lb_f
Torso Flexion (backward)	25	2 ft. lb_f
G. HIP MOBILITY		
Abduction (leg straight)	45	2 ft. lb_f
Adduction (knee bent)	30	2 ft. lb_f
Abduction (knee bent)	35	2 ft. lb_f
Rotation (sitting): Lateral	30	2 ft. lb_f
Rotation (sitting): Medial	30	2 ft. lb_f
Flexion	115	2 ft. lb_f
Extension	35	2 ft. lb_f
H. KNEE MOBILITY		
Flexion (standing)	110	1 ft. lb_f
Rotation (medial)	35	1 ft. lb_f
Rotation (lateral)	35	1 ft. lb_f
Flexion (kneeling)	155	1 ft. lb_f
J. ANKLE MOBILITY		
Extension	40	3.0 ft. lb_f
Flexion	35	3.0 ft. lb_f
Abduction	25	3.0 ft. lb_f
Adduction	25	3.0 ft. lb_f

WEIGHTLESSNESS - VESTIBULAR FUNCTION

STATEMENT OF THE PROBLEM

The perception of body position and movement is controlled principally by the specialized sense organs in the inner ear, collectively termed the vestibular apparatus or the labyrinthine receptors. These are the otoliths and the semicircular canals. The otoliths are stimulated by linear accelerations (including gravity) and are the specialized organs for the sensory perception of head tilt relative to the direction of the force field. The semicircular canals sense the magnitude and direction of angular accelerations. The brain uses this sensory information to maintain the body's posture.

A number of potential otolithic malfunctions resulting from prolonged weightlessness (followed by re-entry accelerations), were very early postulated:

a. The calcium carbonate otoliths may become dislodged from the otolithic membrane, or the membrane may detach from the hair cells.

b. Individual hair cells may display a disuse atrophy which could lead to either a functional or anatomical degradation, or both.

c. The sensitivity of the otolith organs may increase, exaggerating the effects of small and large accelerations or influencing visual spatial orientation with spurious otolithic sensory "information".

d. The sensitivity of the otolith organs may decrease, thus diminishing the effectiveness of postural muscle coordination upon return to a gravity or gravito-inertial environment.

e. Removal of "normal" stimuli to the otolith organs may produce a loss of general muscle tone which in turn would contribute to muscular incoordination, loss of strength, and work task ability.

f. Changes in otolithic neural outflow may inhibit or facilitate semicircular canal responses. Although canal responses are now of questionable significance in the weightless state, they would be of overwhelming importance in a constantly rotating space station where the symptoms of motion sickness would seriously compromise the operational effectiveness of crewmen.

The confirmation or negation of these potential dysfunctions as well as their relationship to motion sickness remains for future long duration space flights to determine. It should be noted that the motion sickness symptoms of early Soviet flights and of Apollo 8 and 9 were not anticipated.

The importance of the vestibular organs in the performance of tasks becomes apparent if one considers their neuro-anatomical connections to the following:

a. Reticular system, dealing with alertness and attention.

b. Eye muscles.

c. Autonomic nervous system, dealing with regulation of respiration, heart rate, Gl tract motility, etc.

d. Voluntary and "Anti-Gravity" body muscles.

e. Cerebral cortex.

Experimentally produced discrepancy between visual, vestibular and tactile-kinesthetic spatial perceptions leads to a stressful sensory conflict which, depending on the individual, produces symptoms ranging from disorientation to nausea and vomiting. The problem is to understand the effects of prolonged weightlessness on the vestibular organs and associated tactile-kinesthetic functions of both astronaut and non-astronaut populations, and to establish the significane of these effects during subsequent exposure to re-entry acceleration and normal gravity conditions.

PAST MEDICAL APPROACH

Following are some experiences of significance to labyrinthine and proprioceptive function, which have been noted during weightless manned space flight.

During the first American orbital flight (MA-6 February 20, 1962) Astronaut Glenn experienced an illusion of tumbling forward after cessation of the initial acceleration of his vehicle and entry into the weightless environment. He also noted a false sensation of accelerating in a direction opposite to retrorocket firing prior to re-entry.(2)

Astronaut Cooper, during the initial stage of his Mercury flight, (MA-9, May 15, 1963), felt "... somewhat strange for the first few minutes ..." after which he "readily adapted" and felt "completely at ease". Later, he awoke after a short nap, "with no idea where I was and it took me several seconds to orient myself". He had the same experience again and noted that, with respect to sleep, "you have trouble re-grouping yourself for a short while when you come out of it". He had an experience, similar to Astronaut Carpenter's on an earlier flight (MA-7, May 24, 1962), when the cockpit seemed to be "somewhat differently located in respect to myself", upon on-set of the weightless state. He felt, during the early part of the first obit, a moving forward in the seat in spite of tightly fastened restraint straps and that the equipment stor-age kit on his right seemed at a different angle relative to him than when on the launch pad. He felt that he was sitting upright although he later described a feeling of hanging up-side down because of pressures against his shoulder straps. He noted that he did not feel "completely at home" and that he had not adjusted to his new surroundings until after the first half of the first orbit.[6]

The sensation of hanging upside down from their restraint straps was also noted by Russian Cosmonauts Yeganov and Feoktistov (VOSKHOD 1, October 12, 1964) but were similarly brief and always disappeared upon the onset of re-entry acceleration. Cosmonauts Gagarin (VOSTOK 1, April 12, 1961), Titov (VOSTOK 2, August 6, 1961) and Popovich (VOSTOK 4, August 12, 1962) also briefly experienced this inversion illusion during their space flights but the phenom-enon was reported to have had no effect on their performance.[5] These reports all suggest that the sudden freedom of the otolith and proprioceptive organs from their normal gravitational stimuli induced sensory experiences similar to the oculogravic illusion resulting from jet aircraft level off and to the inversion illusion described from "zero gravity" aircraft flights.[3] In general, the flight training and prior parabolic flight maneuver experiences of Soviet cosmonauts have been directly related to the appearance of such inverted feelings, with the least experienced pilots reporting the greatest effects.

A more significant feature of early Russian space flight experience was the apparent motion sickness syndrome reported by Titov during VOSTOK 2. After five or six orbits he noted symptoms of decreased appetite, giddiness, and nausea which were aggravated by sharp head movements and reduced by keeping his head still. In spite of the fact that the vehicle was probably rotating slowly and that repeated head movements combined with anxiety and the initial inversion experiences could theoretically account for the problem, the results were interpreted as from a direct "otolithic-vegetative" disorder.[1] Subsequently, a great deal more investigation and training was devoted to the labyrinthine and proprioceptive systems in the Soviet space effort with somewhat ambiguous results. Symptoms as dramatic as Titov's were not again reported until the flights of Apollo 8 and 9, although temporary motion sickness was apparently experienced in a milder form by both Feoktistov and Yegarov. The eight and fourteen days of Gemini V (August 21, 1965) and Gemini VII (December 4, 1965), respectively, produced no such symptoms in the four U. S. astronauts involved, although they experienced an increased G sensitivity during retrofire and re-entry. This apparent form of increased vestibular sensitivity disappeared postflight. Another inflight finding was that measurements of the visually perceived "horizontal" (a process depending on both visual and vestibular sensations) were significantly more stable than under earth gravity.[4] The result is consistent with Cosmonaut Popovich's reports of improved hand steadiness in sensory motor drawing tasks during weightless space flight[7] and suggests that at least for short duration flights, the vestibular control system is not seriously affected. However, we cannot reliably predict labyrinthine and proprioceptive effects for long duration space flight from the small number of subjects studied during short duration flights.

Finally, the nausea and vomiting which occurred during the Apollo 8 and 9 flights was almost certainly due to vestibular system malfunctions. The relationship between these symptoms and the greater freedom of intravehicular movement in the Apollo CM deserves careful attention.

PRESENT MEDICAL POSITION

One of the biomedical goals of extended manned space flights will be to establish experimentally (1) which of the above-mentioned vestibular reactions consistently occur; (2) which are merely transient phenomena of little operational significance; and (3) which might lead to a progressive deterioration with phenomena will lead to an increased understanding of vestibular organ physiology which would never be possible under the earth's gravitational influence. These studies can best be done in an earth orbital space station of up to six months duration.

Because of our inability to produce conditions of prolonged weightlessness on earth, at least two major areas of vestibular investigation are necessary for the qualification of man in long duration space flight:

a. Ensure that permanent otolithic changes attributable to space flight conditions do not occur.

b. Ensure that temporary vestibular disturbances will not occur inflight that will interfere with crew safety and mission success.

These areas are also significant to the study of man's adoption to rotating space vehicles.

FUTURE EFFORTS

Ground based studies should include:

a. Development of a standardized series of otolithic, visual, tactile and kinesthetic laboratory tests for astronauts, some of which can be administered periodically in flight.

b. Semiannual testing of the entire astronaut population.

c. Pre-, in-, and postflight administration of these tests on all astronauts involved in missions of over ten days.

d. Development of counter-measures in case of revealed problems.

Inflight studies should include:

a. Otolithic dependent visual responses.

b. Tactile/kinesthetic responses.

c. Semicircular canal thresholds and responses.

d. Validation of counter-measurers.

Close coordination with the Ames Frog Otolith Experiment, perceptual and visual studies, bone and muscle studies, cardiovascular studies, sleep studies, and studies of crew movements and vehicular accelerations should also be maintained.

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IONIZING RADIATION

STATEMENT OF THE PROBLEM

Ionizing radiation possesses sufficient energy to create charged particles during absorption by and interaction with matter. Exposure of biological materials to any ionizing radiation may disrupt cellular processes and impair normal functioning.

Inasmuch as a single ionizing event can produce molecular change, it appears that there is no threshold for radiation injury at least at the molecular and cellular levels. The effect at higher levels of biological organization vary considerably depending on the quality and total amount of radiation absorbed.

The radiation environment in space may include many sources:

1. Natural radiation.
2. Secondary radiation (produced by interactions of the primary natural radiation with the shielding material of the space vehicle).
3. Radiation from onboard nuclear power sources.
4. Radiation from man-made, high-altitude nuclear detonations.

Of these, the last three are under man's control. Natural space radiation is not amenable to such control and consists of three components:

a. Galactic cosmic rays. These are principally proton and alpha particles with an admixture of heavy ions. Their fluxes are well known but the radiobiological effectiveness for heavy ions is uncertain.

b. Geomagnetically trapped radiation. This arises from the electron and proton fluxes confined in the Van Allen belts. Exposure is spatially localized and its magnitude depends on the manner in which the belts are traversed.

c. Solar flare events. These consist of protons and alpha particles emanating from the sun and are most difficult to control. Solar flare events apparently occur randomly and are not presently predictable with any useful accuracy. In addition, calculations of particle flux and spectrum cannot be obtained with an accuracy of better than a factor of two.

Radiation effects are highly dependent on exposure conditions and vary from minor symptoms such as fatigue, malaise and slight nausea, to more serious complications such as vomiting, diarrhea, anemia and even death. Total dose, dose-rate, depth-dose distribution, region of body exposed and type of radiation are some of the most important injury modifying factors.

Radiation effects on the complex mammalian organism, may be divided into two general categories: somatic and genetic.

Somatic effects are those manifested directly by the recipient of the radiation and may be divided into (a) early effects appearing between minutes and 60 days following irradiation, and (b) late effects appearing only after many months or many years.

Genetic effects, by contrast, do not show up directly in the irradiated organism but, rather, in its progeny via modification to the germinal tissue. It is doubtful if genetic considerations will be an important constraint to manned space flight due to the small astronaut population involved. Genetic hazard is based primarily on the detrimental effects resulting from irradiation of large populations.

In terms of mission performance, the early radiation effects may be important during short duration space missions. On the other hand, late or delayed effects can become important during long duration missions and are pertinent to the general lifetime well-being of the flight personnel as well as to the actuarial risk of space flight as a career. It is important, then, that steps be taken either through shielding, operational procedures, or both, to restrict the radiation exposure of the astronauts to as low a level as possible.

PAST MEDICAL APPROACH

The problems associated with exposure to ionizing radiation were recognized even before the inception of X-ray machines but after many of the early pioneers died due to the lack of adequate protection. Prior to NASA's inception and during the development of the nuclear era, the Atomic Energy Commission, the

Department of Defense, and the U. S. Public Health Service accomplished much basic research in radiological health in conjunction with development of the nuclear industry and nuclear weaponry. Today there exists a very large body of scientific data which gives basic information as to the hazards to be expected from radiation exposure. While much of this information is readily applied to problems associated with space exploration it does not precisely cover the dose rate, flux characteristics, and radioactive particle energies encountered in space missions. To gain this knowledge NASA is now conducting additional basic research.

In all missions to date no astronaut has received a biologically significant dose.

PRESENT MEDICAL POSITION

As NASA embarks on more extensive space exploration manned missions will necessarily be of longer duration and have less capability for immediate recall. The probability of appreciable radiation exposure will increase.

Despite the abundance of radiological health research, major refinements in the available information are still needed. Currently, the absorbed radiation dose received by the astronaut can be predicted only within a factor of two. Further, the response to a radiation dose by any specific individual can be predicted only within a factor of two. It is obvious that greater precision is required to establish safe radiation exposure standards.

An approach for establishing radiation protection criteria has been developed by the Space Radiation Study Panel of the Space Science Board, National Academy of Sciences. According to this approach, summarized in the Appendix, the significant medical symptomatology or responses to crew safety and mission success are first defined and then related to radiation dose levels. Acceptable responses are subsequently established according to a risk versus gain philosophy and judgment. The results of this judgment vary generally for each mission.

The following guidelines should be employed in defining acceptable responses for all missions. Other criteria may be adopted for specific missions.

a. Any amount of radiation should be considered potentially detrimental and, therefore, exposure must be kept at a minimum consistent with a risk versus gain trade-off.

b. Radiation exposure should be kept below the level which might result in an unacceptable probability of inflight response through which crew safety or mission success could be jeopardized.

c. The re-use of previously exposed, experienced crewmen should be governed by the nature and extent of previous exposure, the predicted exposure risk of the mission and the importance that is placed on having any previously exposed crewman engage in a particular flight.

d. Any radiation exposure that might exceed the dose limits prescribed for the mission will be permitted if the concomitant hazard incurred by actions to avoid the exposure or to protect oneself against the potential injury is determined to be greater than the hazard associated with the excess radiation dose.

e. With regard to late effects, the selection of dose limits for early effects will automatically entail the acceptance of certain probabilities for the occurrence of generalized life shortening, leukemia, and other late manifestations. Unfortunately there is no easy way of approaching the problem of setting acceptable limits for the long term effects that does not also imply certain career-dose limits which cannot be currently established.

Radiation exposure levels can be selected according to the following operational criteria:

Planning Operational Dose (POD): The dose which should not be exceeded without requiring a mission modification of some degree. The degree of modification will be a function of the magnitude of the excess dose and will be formulated by mission rules. This dose will be used for mission planning purposes to determine if proposed trajectories and time lines are acceptable.

Maximum Operational Dose (MOD): The dose which should not be exceeded without specific modification of the mission to prevent further radiation exposure. Such an exposure would be considered to result in a potentially harmful response in terms of crew safety or postflight, in terms of delayed radiation injury.

Each dose level is divided into an early (inflight) and a delayed (postflight) response. Early responses are considered to involve the gastrointestinal system and the skin. Delayed responses are considered as those of the hematopoietic system, the lens of the eye, and the summation of the carcinogenic/ life-shortening effects. In the determination of dose limits, each response and its effect on the mission and crew is considered independently, and no adjustments are made for known or suspected uncertainties in radiobiological data shielding calculations, or environmental data.

FUTURE EFFORTS

Among the more important problem areas requiring further research for long term manned space flight are the following:

a. Continued effort in definition and predictions of the space radiation environment, particularly in terms amenable to assessment of radiation effects on living systems.

b. Collection and organization of data on human response to acute and chronic whole-body radiation exposure.

c. Investigation of the dose-time-intensity dependency of the radiation response of man.

d. Investigation of the degeneration and repair of the hematopoietic system under acute and semi-acute radiation exposure conditions.

e. Continuation of investigations of the biological effects of high-energy charged particles and determination experimentally of the dynamics of early skin response to protons and alpha particles of sufficient energy to penetrate the epidermis.

f. Further investigation of the influence of non-homogeneity of dose distribution (both surface and depth) on early and late response to acute and semi-acute radiation exposure.

g. Investigation of the effects of combined stress, especially the possible interface between weightlessness and the response to radiation exposure.

h. Continuation of the development of more sophisticated dosimetry directed toward producing measurements amenable to correlation with biological effects and expressed in units useful for prediction of specific radiation response.

i. Investigation of the cumulative efforts of heavy charged particle interactions with biological systems and the significance of neural and behavioral response to acute and chronic radiation exposure.

j. Continuation of the search for drugs that are of practical prophylactic and therapeutic value against early and delayed radiation effects.

k. Development of emergency radiation protection techniques such as partial body shielding or similar measures.

APPENDIX

EVALUATION OF POTENTIAL RADIATION HAZARDS IN MANNED SPACE FLIGHT OPERATIONS

Synopsis of a study made by the
Space Radiation, Panel, Space Science Board,
National Academy of Sciences*

1.0 INTRODUCTION

The Federal Radiation Council recognizing the inherent limitations of the "Maximum Permissible Dose" concept, has officially introduced a much more flexible approach to the problems of radiation protection. This philosophy accepts the non-threshold concept of radiation injury and establishes the underlying principle that permissible radiation exposure is fundamentally a balance between the risk of radiation injury on one hand and reasons for accepting the exposure on the other.

In anticipation of cislunar and interplanetary manned space flights the Life Sciences Committee of the Space Science Board, National Academy of Sciences - National Research Council established a study panel to evaluate the biological problems associated with space radiation.

The establishment of a guideline for protection against radiation is clearly needed in order to avoid unacceptable risk to the flight crew and jeopardy of the mission. The choice, however, of protection criteria that are too restrictive may,

*Publication 1487, 1967.

through their interaction with other safety features of the spacecraft and the mission, defeat both of these objectives.

Based on these considerations, the Panel did not recommend "permissible doses" for space operations. Rather, the Panel provided - to the best of its ability - a quantitative description of the range of radiation risks assignable to different combinations of radiation exposure and described the upper limits of human tolerance to such exposure. In adopting this approach the Panel recognized that, under the guidelines of the Federal Radiation Council, the responsibility for making the ultimate balance between potential risk and anticipated gain is an integral part of mission planning and approval, for which the operating agency is accountable.

The following text summarizes the approach for the determination of radiation protection criteria for manned space flight operations as suggested by the Space Radiation Study Panel.

2.0 RADIATION RESPONSE CRITERIA AND THEIR APPLICATION TO HAZARDS EVALUATION

The Panel suggests that the space radiation hazards be evaluated in the following terms:

a. Immediate or early performance decrement (early responses) occurring within a few hours to one month following a major exposure.

b. Progressively increasing performance decrement or serious loss of performance over long periods of flight as a result of an accumulating exposure (progressive injury to the blood-forming system).

c. Probability of delayed or chronic radiation response that may require interrupting a planned series of flights and which may limit an astronaut's career.

Within each of these categories, the significant clinical symptomatology or responses must be defined on the basis of importance to crew safety and mission success. The relative significance to responses will be mission-dependent. The following suggestions may assist in identification of the important responses and in evaluation of their significance for each specific mission:

(1) Any amount of radiation exposure should be considered as potentially detrimental and, therefore, the exposure should be kept at a minimum. Consistent with the risk versus gain philosophy.

(2) Radiation guides should be set below the level that might result in an unacceptable probability of in-flight response capable of jeopardizing crew safety.

(3) Elapsed time between recurrent or repeat use of an individual or crew should take into consideration the nature and extent of previous exposure, the predicted exposure risk of the contemplated mission, and the degree to which mission success may depend on individual or crew experience.

(4) The dose or doses established for early effects automatically entails acceptance of certain probabilities of occurrence of generalized life shortening, leukemia, and other late manifestations.

(5) The radiation responses may be subdivided into "in-flight" and "post-flight" categories. although this subdivision is somewhat arbitrary, it is time-dependent and may be important under special circumstances, for which certain higher risks may be acceptable if it is clear that the latent period for expression of injury will automatically cause the response to occur post-flight.

2.1 Early Performance Decrement

2.1.1 Dose-Response Relationships

Early radiation responses considered most pertinent to evaluation of early performance decrement are summarized below. The user is cautioned, however, to realize that all dose estimates are provisional and that estimates of the 10 and 90 percent response levels may be in error by ± 50 percent or more. Errors at the 50 percent level may be somewhat less. The selection of these response levels, in fact, is an attempt to provide guidance in a range compatible with general clinical experience. Space radiation response predictions may be additionally uncertain due to the uncertain physiological impact of other physical stresses associated with flight activity.

Prodromal Reaction

Prodromal symptoms (e.g., anorexia, nausea, vomiting, etc.) may appear in less than one to two hours ($T_{50} \sim 2.5$ hours) of exposure and subside in less than one to two days. The estimated dose levels for brief high-intensity radiation exposure (assuming QF* = 1) are given in Table 1.

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*Quality factor

Hematological Depression

Early signs or symptoms of damage to the blood-forming system (e.g., lymphopenia, neutropenia, thrombocytopenia) begin to appear within one to ten days (depending on dose and circulating blood cell component) after onset of a significant bone marrow exposure. In this case, signs and symptoms may appear after significant exposure even when the dose is protracted over several weeks. Response levels for depression of the hematopoietic system are usually given as percentages of normal peripheral blood count versus dose. Such percentages are mean response levels of the population, not measures of the probability of response. Extreme day-to-day fluctuations in both the normal and pathological states preclude expression of the latter terms. Estimated absorbed whole-body dose values for production of 25, 50 and 75 percent levels of blood count depression (at time of maximum) are given in Table 2. For purposes of specifying dose, it is assumed that the point of interest in the average functional depth of the bone marrow (5 cm) and that the QF of the radiation is unity.

From a prognostic point of view a 25 percent depression of circulating blood elements is indicative of early radiation damage to the blood-forming organs. A depression of 75 percent and greater is definitely to be avoided as it is getting into the dosage range of probability of early radiation lethality.

Hematopoietic Lethality

Lethality in the dose range of interest in space missions is an augmentation (with increasing dose) of bone marrow depression with consequent infection and hemorrhagic diathesis. Signs and symptoms begin within a few hours with the prodromal reaction, followed by progressive hematological depression terminating in death in 2 to 8 weeks, depending on the dose. Estimates of absorbed doses of high-intensity whole-body radiation for production of the 10, 50 and 90 percent response probability levels are given in Table 3. The point of interest for dose estimation is the approximate midline of the body ($\sim$ 11 cm depth), and the QF is taken as unity.

Skin Erythema and Desquamation

Under conditions of light shielding, such as during extravehicular operations or operations in the lunar landing module, a high-intensity exposure of the skin with little deep tissue dosage may occur. Depending on radiation quality, dose, and dose rate, erythema may appear within a few hours to several days. With larger doses, there will be erythema that progresses to dry and then to moist desquamation. The restrictions and abrasive contacts of a space suit may make a moderate erythema over even relatively small areas of the body quite uncomfortable and result in considerable performance decrement. Table 4 gives the estimated absorbed doses of high-intensity radiation for production of 10, 50 and 90 percent probability of early skin response when the area exposed is 35 to 100 cm^2. The point of interest for dose estimation is taken as 0.1 mm depth.

Reaction to General Physiological Injury

Loss of ability on the part of a crewman to perform normal duties through reaction to general physiological depression (e.g., lassitude and fatigability) may occur. Ill-defined effects that reduce normal performance accompany all stages of acute radiation injury and are expected to be a concurrent response at the dosage level of radiation eliciting the prodromal responses.

2.1.2 Dose-Response Modifying Factors (Early Responses)

Quantitative evaluation of the factors that modify radiation responses is singularly the greatest uncertainty in establishing human response criteria for space radiation exposure. The most obvious modifying factors are radiation quality, dose rate (as influenced both by protraction and fractionation), and dose distribution (both topical and depth). For space applications it is suggested that "dose equivalent" in "rems" used in conventional occupational radiation protection, be replaced by "reference equivalent space exposure" (RES) in "reference equivalent units" designated "reu". Conceptually, the method of evaluation is the same as that employed in conventional radiation protection. The space radiation dose (D) is multiplied by a radiation quality factor (QF) and subsequently by other appropriate modifying factors to give the reference equivalent space exposure:

$$\text{RES (reu)} = \text{D (rads)} \times \text{QF} \times (f_1, f_2 \cdots f_n) \qquad \text{(Eq. 1)}$$

where $f_1 \cdots f_n$ are the appropriate modifying factors for the particular response being evaluated. In principle, this procedure is applicable to evaluation of both early and late radiation responses. However, inadequate knowledge of the quantitative influence of the relevant modifying factors and their interdependence necessitates the choice of a set of values for each specific situation on the basis of rather arbitrary simplifications and generalizations.

Quality Factor

QF_E values for early responses are given in Table 5. In summarizing the available information, it appears that little error will be introduced by applying a QF_E of unity to space radiation in general when considering early performance decrement from high-intensity space radiation exposure. Responses of the skin and perhaps of the germinal epithelium constitute exceptions under conditions of light shielding.

Because of the spectral characteristics of the principal space radiations, skin reactions are significantly influenced by radiation quality under actual operating conditions. Maximum dose and LET* (and thus maximum QF_E) will occur near the body surface. For the skin, the point of interest is the basal layer at a depth of only 0.1 mm. The lighter the shielding, the greater will be the contribution of the high LET component to the total skin dose. The reference equivalent space exposure (RES) for skin responses, therefore, should be determined for each specific case taking into account the local mean LET spectrum at 0.1 mm depth assuming $QF_E = 1$ for components of $\leq$ 3.5 kev/μ and $QF_E = 3$ for all components $\geq$ 20 kev/μ. A linear relation between QF_E and LET may be assumed between these limits.

Dose Distribution

Dose distribution in space radiation exposure will be highly non-uniform with respect to depth, area, volume, and region or organ systems exposed. In this case, it is possible

*Linear Energy Transfer

only to make very arbitrary simplifying generalizations. With respect to depth-dose distribution the acquired dose is calculated or measured at the average depth or anatomical site of interest for the particular response.* The point of interest for skin responses is at a depth of 0.1 mm, for hematological depression a depth of 5 cm, for hematopoietic lethality a depth of 11 cm, and for prodromal response and general physiological injury a 15 cm diameter sphere in the mid-epigastric region.

With regard to region or volume exposed it is suggested for prodromal, hematological and early lethal responses a dose involving a major portion of the trunk be considered as capable of eliciting full response and be assigned a "volume factor" (f_v) of one. Exposure of the extremities exclusive of the trunk would be much less effective. Based on fraction of total body mass and active bone marrow, an arbitrary choice of a f_v of 1/5 might be suggested for the extremities.

Skin and germinal epithelium responses must be considered specifically. A sharp response of even a small skin area, regardless of location, could be highly uncomfortable particularly under a space suit. Furthermore, dose values given in Table 4 were established for skin areas of $\sim$35 to 100 cm^2, and early erythema and desquamation are somewhat area-dependent up to $\sim$300 to 400 cm^2. The area-effectiveness factor (f_a) of $\sim$1.25 be applied to the doses given in Table 4 when exposure involves skin areas greater than 150 cm^2.

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*Under these conditions of dose expression, the depth-dose distribution or penetration factor (f_p) is assumed to be unity for the evaluation of RES.

In the case of the germinal epithelium response is considered a local effect. Because of the limited size and localization of the testicles, it is reasonable to assume that they either will or will not be in the exposure field in which case f_r will either be unity or zero. In mentioning the germinal epithelium it is emphasized that the response in this case is considered of no significance in evaluating risk or early performance decrement.

Dose Protraction

The effect of dose protraction has been studied to some degree for most of the above early signs and symptoms; therefore, some suggestions are possible regarding general "dose-effectiveness" factors (f_r) that are useful for exposure periods up to three or four weeks. To derive the factors, it was assumed that the decrease per rad in biological effect associated with a dose-rate decrease can be compensated for by an increase in total dose required to produce the given effect. Thus the ratio of total doses required for low dose-rate versus high dose-rate exposure will determine the "dose-rate-effectiveness" factors. This is not the same as taking a ratio of dose rates, however, since for some tissues the latter may change by a factor of 10 or more while being accompanied by a change in effect of only about 2. There is also considerable difference in protraction period over which the change from maximum to minimum effect occurs in the various tissues and systems. Table 6 attempts to encompass all of these variables for exposure periods varying from a few hours to a few weeks with respect to total doses high enough to elicit the more significant early responses. The rate-effectiveness factors (f_r) are given as the reciprocals of the ratios of total doses.

The terms "high" dose rate and "low" dose rate are difficult to define for all situations. What is considered a high and a low dose rate for early responses might be quite different from high and low dose rates for progressive and late responses. Furthermore, a high and a low dose rate for early skin responses might be different from those for early hematological and prodromal responses. In general, Table 6 attempts to take these variations into consideration for the important early responses. As an example of the use of this table, a given prodromal sign (e.g., nausea) may have a 10 percent probability of occurrence following an exposure of 50 rads delivered over 2 to 4 hours (dose rate 12 to 25 rads/hr), while an exposure of 125 rads (2.5 x 50) would produce the same probability of response if the dose was protracted over 2 to 4 days (dose rate 30 to 60 rads/day). It is suggested, therefore, that the space radiation dose (D) be multiplied by the appropriate rate-effectiveness factor (f_r) from Table 6 to evaluate RES when exposures are protracted over periods comparable to those specified.

Radiation recovery rates are influenced by LET and for this reason, the f_r values given in Table 6 are specified for low-LET radiations. Technically, the rate-effectiveness factors should be applied only to the low-LET components of space radiation. Correction of f_r for LET appears unnecessary under shielding conditions that result in only a small fraction of the absorbed dose at the site of interest being delivered at high LET. Information on early skin responses suggests, however, that the slopes of the time-dose response curves decrease with increasing LET. For early skin responses under exposure conditions of very light to nominal shielding, where from ∿10 to ∿75 percent of the absorbed dose at 0.1 mm depth from solar flare events may be due to densely ionizing components, adjustments should be made by assuming f_r is unity for that fraction of the dose delivered at or above some arbitrary cut-off for high LET (e.g., ∿15 kev/μ).

2.1.3 Example of Evaluation of Early Risk

Application of the information given in this section to an evaluation of a risk of early performance decrement may be illustrated (using skin erythema as the early response) by a hypothetical mission during the triplet solar flare event of July 10-16, 1959. No attempt is made to make the assumptions conform necessarily to the actual conditions. If it is assumed that the average effective shielding of the spacecraft was 2 g/cm^2, the accumulated skin dose (D) during the 6 day period of the triplet flare would have been 674 rads. Let it be assumed also that the QF_E was 1.45, the skin area involved was a major portion of the front surface of the body, the dose received was measured at a depth of 0.1 mm, and 25 percent was delivered at an LET of ∿15 kev/μ. Under these conditions, $QF_E = 1.45$, $f_a = 1.25$, $f_p = 1$, and $f_r = (1/3 \times 0.75 + 1 \times 0.25) = 0.5$. The reference equivalent space exposure, evaluated from Eq. 1, would be:

$$\text{RES} = 674 \times 1.45 \times 1.25 \times 1 \times 0.5 = 611 \text{ reu} .$$

Since 1 reu is equivalent in effectiveness to 1 rad of reference radiation, comparison of RES with the reference radiation dose-response relationship given in Table 4 suggests that the probability of an erythema response under the specified conditions would have been of the order of 50 percent.

2.2 Progressive Performance Decrement

The possibility of radiation-induced progressive performance decrement will increase with increasing mission duration. The highest intensity exposures will occur very infrequently and then only over a period of a few days, such as during solar flares. Most exposures to radiation in space flights are, therefore, expected to be at low dose rates. Since radiation effects decrease roughly proportionately with decreasing dose rate, the early effects described above for high-intensity exposures will become less marked or even absent under sufficiently protracted exposure, even though the dose rate during an occasional episode may be relatively high. Under these conditions, more subtle effects may occur as a result of a gradually accumulating injury to the blood-forming tissues that may be accompanied by a reduction of the space crew's ability to maintain normal flight operations. This injury may be characterized by vague symptoms of fatigability, headache, dyspnea, reduced resistance to general stress, increased incidence of low-grade infection, and decreased blood-oxygen transport.

Except after very high doses, radiation injury is comparatively slow to produce symptoms, and these may emerge progressively and then subside. The expressions of injury and recovery, therefore, are concurrent. When the exposure is essentially continuous but at a low daily rate (perhaps 1 rad/day or less for man), the rate of injury and recovery will undoubtedly approach equilibrium, and a steady state may be maintained for long periods. Although the phenomena of equilibrated injury and recovery have been quantitatively defined in experimental animal populations under specific conditions of exposure, the kinetics of injury and recovery for man cannot yet be given with any degree of confidence.

Prediction of man's response is difficult even when a regular pattern of protracted or fractionated exposure is involved. The erratic pattern of exposure that may occur in most projected space flights and the accompanying moderate to serious depth-dose inhomogeneity make extrapolation virtually impossible at present. Sufficient dose protraction (whether by low dose-rate or by fractionation) will certainly lessen or even preclude the occurence of prodromal symptoms and early skin responses. Attention will therefore be restricted to injury to the blood-forming tissues. The important questions are to what extent damage to the bone marrow system will be lessened and what time factors are involved.

In the absence of any well substantiated method of estimating an individual's residual radiation damage from intermittent exposure and his capacity to tolerate additional doses, the Panel suggests that a dose-accumulation procedure as outlined below be utilized. The procedure allows for any changing effectiveness of accumulating dosage by taking dose-rate into account. Although there are insufficient data to make this evaluation with a high degree of precision, the Panel feels that some evaluation of dose-rate effects under the anticipated conditions of exposure is important in determining the radiation status of a space crew. A suggested approach is outlined below:

(1) Radiation absorbed by a crew on a deep space mission will typically result from occasional limited periods of exposure at elevated dose rates (which will vary from period to period and with time during each period) superimposed on a continuous low dose-rate ambient cosmic radiation background. The irregularities in dose-rate can be smoothed for calculation and accumulated on a mean daily dose basis.

(2) It is assumed that the effect per unit dose will decrease linearly with decreasing dose rate.

(3) For bone marrow responses doses delivered at dose rates of 50 rads/day and above are assumed to produce maximum injury per rad, while exposure at rates of 1 rad/day and below are assumed to produce minimum injury per rad accumulated.

(4) A dose-rate accumulation effectiveness ratio of 3 will be assumed between these limiting dose-rates, and linear interpolations of the accumulation rate factor (RF_A) may be made for all intermediate dose-rates (Fig. 1). RF_A should not be confused with f_r (Table 6) which applies only to early responses within ∿30 days after high-intensity exposure.

(5) The RF_A values taken from Fig. 1 may be applied to the space radiation dose (D) in the general Eq. 1 to derive a value for RES that allows for differences in progressive

bone marrow injury as a result of differences in dose accumulation rate. It is suggested that an operating agency set acceptable mission accumulated exposures on the basis of the lowest dose-rate (1 rad/day or less). This recommendation is consistent with standard practice in occupational radiation protection. In contrast to early responses where the standard exposure situation has always been the high dose-rate experience producing maximum effect, the standard for protracted low dose-rate exposures has always been that associated with minimum effectiveness. Therefore, RES for progressive bone marrow injury will only be subject to upward adjustments by multiplying the space dose (D) by RF_A (which is always ≥ 1) to allow for increasing effect as dose-rate increases above 1 rad/day. As dose-rate and dose accumulation are protracted, expression of bone marrow injury approaches that of late or delayed responses. It seems, therefore, that quality factors for late response (QF_L) should be used for evaluating progressive bone marrow injury. Quality factors for late responses are given in Table 7. Because of the spectral characteristics of the major space radiations and the effective depth of the bone marrow (5 cm). QF_L will usually be equal to or near 1. It is suggested that the contribution of daily dose increments (assuming total-body exposure) to the accumulated RES for progressive bone marrow injury be evaluated as,

$$RES(reu) = D\ (rads) \times QF_L \times RF_A, \qquad (Eq.\ 2)$$

and subtracted from a pre-established acceptable mission reference equivalent space exposure (RES_m) expressed in reu to give a chronological record of the remaining allowable mission exposure.

An example of the manner in which a record may be kept of the accumulated marrow exposure received by a flight crew during a hypothetical 1 year mission is shown in Table 8. In this example, it is assumed that the acceptable RES_m, established on the basis of the risk versus gain philosophy, was set at 250 reu. It is assumed also that exposure involved two traversals of the geomagnetically-trapped radiation fields, continuous space-ambient background ($\sim$ 0.1 rad/day), and interception of one major solar flare event on the 151$^{\underline{st}}$ day. The example illustrates how such a chronological record may give some feeling as to the progressive bone marrow exposure status of the crew during an extended mission.

The uncertainties in evaluating the risks from space radiation exposure increase disproportionately with increasing mission duration. For missions up to 30 to 60 days, risk evaluation is based on a reasonable amount of factual information. For missions beyond 1 year, evaluation becomes more and more a matter of judgment. In an effort to provide some guidance for long duration missions, suggestions of annual exposure-accumulation factors are given in Table 9. The factors are given as a set of multiples of a 1 year exposure on the assumption that the 1 year exposure is in the range of 200 to 300 reference equivalents (reu). The exposure range is not specified to restrict an operating agency (which has the prerogative of setting any mission risk it is prepared to justify on the basis of risk versus gain) but rather to obtain some degree of Panel agreement on annual exposure-accumulation factors while keeping in mind that risk of late radiation effects is assumed to be directly proportional to accumulated dose. The factors are selected on the judgment that any derived RES values would produce no clinical signs or symptoms of hematological injury (such as infection, hemorrhage, fatigue, or fever) if exposure is generally distrubuted or fractionated over the indicated time periods. The factors do not increase in direct proportion with time; they drop away from simple proportionality to allow for uncertainties of damage to recovery mechanisms and for possible cumulative effects of other stresses associated with space flight.

The Panel feels that present knowledge permits some degree of prediction of what can be tolerated for the general category of progressive bone marrow injury. Although it may be possible to judge from existing experience when a population is approaching the limits of its tolerance (the point where overt signs and symptoms may appear), there is no present way of predicting the variance or distribution of sensitivities that may exist in the population. The variance of the population is an extremely important parameter of any quantitative prediction statement, and present knowledge is far from adequate. In general, the variance may be a function of age, dose-rate, total accumulated dose, post-irradiation time period, radiation quality, presence of other physiologic stresses, and particular tissue or system involved. Since most or all of these factors will be variables in space flight, quantitative and accurate predictions will not be possible. With the above considerations in mind, the consensus of the Study Panel is that a safety factor or uncertainty factor (as the case may be) of 2 may be inherent in the exposure-accumulation multiples given in Table 9. As exposure and time accumulate, the safety factor becomes more of an uncertainty factor because of the gradual shift of the response pattern into the late injury mode. The limiting consideration, therefore, ultimately becomes a matter of the extent of acceptability of long-term effects.

Although it is not possible to avoid all risk of radiation injury, signs and symptoms of early and intermediate injury to the blood-forming system can be selectively avoided by controlling the exposure-accumulation rate. However, the probability of manifestation of late radiation injury such as induction of leukemia and general life shortening will accrue in proportion of the total accumulated exposure.

2.3 Probability of Delayed or Chronic Response

To the extent possible, dose-response relationships are given, and the influence of modifying factors is discussed. As a general operation principle useful over the next few decades, the Panel feels that the probability of such responses as general life shortening and increased likelihood of amlignancy may be considered of secondary importance in evaluation of the risks of manned space flight. This attitude contrasts sharply with evaluation of occupational risks wherein late effects are of primary importance. The relative size of populations provides the major reason for attaching a lesser importance to late effects of radiation injury must be maintained. As noted earlier, selection of acceptable RES values for short-term responses of the gastrointestinal and hematopoietic systems will automatically present certain probabilities for occurrence of leukemia and generalized life shortening and other late manifestations.

2.3.1 Dose-Response Relationships and Risk Evaluation

Late radiation responses are nonspecific in that they cannot be correlated to any particular radiation exposure but must be evaluated in statistical terms in relation to total accumulated dose. It is not possible, under prevailing circumstances, to express late dose-response relationships in a manner exactly comparable to early responses. As with early responses, however, dose associated with a given degree, level, or probability of a specific late response is expressed in rads of a reference low-LET radiation equivalent to 200- to 250-KVP X-rays. Dose-response statements for late responses of most significance and suggestions for late risk evaluation are summarized below.

Late Response of the Ocular Lens

No definite response probability values can be assigned to specific radiation doses for production of lens opacities. It appears that ∿200 rads of reference-quality radiation is the minimum cataractogenic single exposure dose and that some lessening of effect appears to result from dose protraction over a period of at least 2 to 12 weeks. It appears also that a single dose of ∿700 to 800 rads of reference radiation may have a cataractogenic probability approaching unity, 50 percent of which may be progressive resulting ultimately in impaired vision. The slope of the time-dose response curve between single (1 day) exposure and exposure protracted over an average time of $\sim$7 weeks suggests a ratio of protracted dose to single dose of $\sim$2 for the doses required to produce the same level of response. It is suggested that the dose-response relationship shown in Table 10 be considered for space applications. These values may be used in combination with the appropriate QF_L (Table 7) to evaluate RES for late changes in the ocular lens by the expression,

$$RES(reu) = D(rads) \times QF_L \times F_{pr} , \qquad \text{(Eq. 3)}$$

where D is the space radiation dose and F_{pr} is the protraction factor equal to unity for protraction times of 7 weeks and greater and linearly increasing to 2 with decreasing time to 1 day. As an example, if the pre-established acceptable exposure risk for a mission of 7 weeks or longer (F_{pr} = 1) was that corresponding to minimal probability of lens response (RES = 300 reu) and anticipated exposure was to a space radiation with a predicted mean QF_L of 3, the allowable space radiation dose (D) would be 100 rads. If delivered in a single exposure, however, the allowable dose would be only 50 rads.

It should be kept in mind that the greater the level of exposure, the greater will be the probability that any cataracts produced will be progressive, and the shorter will be the latent period before development.

Late Skin Response

Minimal late radiation response of the skin (primarily necrosis) seems to occur at a single high-intensity exposure of about 2000 rads of reference radiation. Table 11 attempts to summarize for operational considerations the standard radiation dose-response relationship for late or permanent skin changes. As with ocular lens changes, the time-dose response curve for skin necrosis suggests a decreasing effect with increasing dose protraction such that the ratio of protracted dose (approximately equally distributed in daily increments over $\sim$7 weeks or longer) to single dose (1 day) required to produce the same probability of response is $\sim$2.3. Equation 3 and the fractionated dose-probability values in Table 11 may be used in combination with appropriate QF_L values (Table 7) and an area-effectiveness factor (F_a) of 1.25 (for areas > 150 cm^2) to evaluate risk from late skin necrosis, assuming F_{pr} is 1 for protraction times of 7 weeks and longer and linearly increases to 2.3 with decreasing time to 1 day. As an example, if the space radiation dose (D) to an area of > 150 cm^2 accumulated (if approximately daily increments) during a mission of 7 weeks or longer (F_{pr} = 1) was 1000 rads of radiation with an average QF_L of 3, the RES would be 3750 reu. Comparison of this value with the fractionated dose-response relationship indicated in Table 11 (on the basis of 1 reu = 1 rad of reference radiation) suggests about a 3 percent probability of necrosis or chronic radiodermatitis. If fractionated more or less equally over 25 days (F_{pr} = 1.65), the probability of necrosis would be of the order of 50 percent

(RES = 6200 reu). In this case, however, the appearance of early skin responses would definitely have been mission-limiting. In evaluating risk from late skin effects, it should be kept in mind that from 5 to 25 percent of cases of chronic radiodermatitis (small areas) progress to the malignant stage and that the area damaged may have a considerable influence on the probability of malignancy.

Life Shortening and Increased Incidence of Leukemia

The Panel's best estimates of the dose response relationships (whole-body exposure of reference-quality radiation) for these late responses are given in Table 12. Any attempts to refine risk evaluations for life shortening and leukemia incidence by adjusting the space radiation dose to give reference equivalent space exposure (RES) probably is not justified in view of the large uncertainties in the dose-response relationships. It is possible, however, to make such adjustments of RES for life shortening and to record chronologically the risk status using Eq. 2 and Fig. 1 in the manner suggested for progressive bone marrow injury. Because of the effective tissue depth (t cm), QF_L for the major space radiations (inside current spacecraft shielding) for production of life shortening and increased leukemia incidence will be approximately unity. QF_L, however, may be estimated from Table 7. A dose-rate accumulation-effectiveness factor (RF_A) may be taken from Fig. 1. To evaluate the life shortening and increased leukemia incidence probabilities, it is necessary only to multiply RES(reu) by the respective probability values for low-intensity reference radiation exposure. The accumulated dose-rate-probability relationships for life shortening and increased incidence of leukemia are shown graphically in Figs. 2 and 3, respectively.

Genetic Manifestations

The radiation effect upon the spermatogenia is reflected as functional response in the seminal fluid some 46 to 70 days post irradiation as a drop in sperm count. Sufficient depression of spermatogenesis will result in decreased fertility or sterility that may persist for months, years or perhaps permanently, depending on the dose. In general, 15 and 100 rads appear to be about the threshold dose for production of oligospermia and azoospermia, respectively. The permanently sterilizing acute dose of radiation for man is believed to be of the order of 500 to 600 rads. Genetic manifestations appear radiation quality (LET) dependent and, therefore, it may be advisable to use the QF-LET relationship given in Table 7 when considering the response to the germinal epithelium to the LET components to space radiation. For purposes of effective dose calculation and measurement the average depth of the tests is assumed to be 2.5 cm. The fact that the radiation effect on germinal epithelium is predominantly a direct one suggests the feasibility of local shielding, if necessary to lessen the probability of response.

Knowledge of the gonad dose would permit calculation of an estimated probability of mutation induction in the spermatogonial cells of the individual and of its expression in the offspring. Such a calculation assumes reasonable knowledge of the following parameters:

(a) The mutation rate per rad per gene ($\sim 5 \times 10^{-8}$)

(b) The number of genes per haploid set ($\sim 10^{4}$)

(c) The probability of expression of the new mutation in the first generation heterozygote ($\sim 5 \times 10^{-2}$)

(d) The gonad dose (D).

Thus, the probability that a new mutation would be observed in the immediate offspring is given by

$$R \approx 2.5 \times 10^{-5} D$$

Since advance cell stages (i.e., spermatocyte, spermatid and spermatozoa) are more sensitive to radiation damage than the spermatogonia or stem cells, it should certainly be recommended that caution be taken to avoid the conception of offspring during the post-flight period in which irradiated post-genial cell stages are still present.

Widely fractionated low dose rate exposures comparable to most in-flight possibilities would probably approximate continuous low dose rate exposures in their mutagenic efficiency, but these rate and interval parameters have not yet been tested. Concurrently there are few data available on the effect of different LET radiations on mammalian genetic end points and any judgment made today will certainly prove premature.

2.3.2 General Considerations of Late Responses

Factors other than those mentioned above modify late radiation responses discussed in the previous section. One of the most important is dose distribution. Present knowledge is not adequate for quantitative evaluation of the effect of unequal dose distribution on probability of life shortening and leukemia incidence. It is possible only to say that partial-body exposure is much less effective than whole-body exposure and, as a first approximation, may be crudely proportional to the relative mass of the body exposed. The effect of area on malignant progression of permanently damaged skin is a troublesome and speculative question. Radiation is known also to produce increased incidence of other types of neoplastic disease other than leukemia (thyroid tumors, osteosarcoma, etc.).

There is no obvious interim approach to the problem of developing radiation guides for evaluating long-term risk without also establishing career exposure limits. Since a lack of radiobiological knowledge and operating experience precludes suggesting establishment of such dose limits at this time, an alternate suggestion is offered as an approach at least with respect to general life shortening. The long-term radiation risk may be compared with the accepted risks associated with piloting high-performance aircraft. It has been estimated that the latter occupation is characterized by an approximately 10 year lift-shortening probability. If this risk is assumed to be additive with the radiation hazards, the question then becomes how much added life-shortening probability might be acceptable.

Lastly, the Panel suggests that records of radiation exposure be carefully maintained. These records should indicate, whenever possible, the dose in rads at critical tissue levels (skin, bone marrow, eyes, etc.), attendant average daily dose-rate, energy and particle spectrum (at least in broad intervals), and extent of partial-body shielding. Such data will be critical for decisions regarding re-utilization of crews and for predictions of probability of long-term effects.

3.0 EFFECTS OF RADIATION COMBINED WITH OTHER STRESSES

The combined stress problem in prolonged space flight is particularly troublesome, since the man-machine loop cannot draw upon the restorative forces of rest, repair and replacement.

The stresses themselves fall into three principal categories: (1) the dynamics of space flight, including the launch and re-entry modes; (2) the internal or cabin environment, including the individual's physiological status; and (3) the external environment of space. The only external environmental factor with which we are concerned here is radiation. The internal environmental factors under consideration are ambient temperature; oxygen partial pressure, noise; physiological factors, including both latent and subclinical infection; and emotional factors. Flight dynamic factors are vibration, acceleration and weightlessness, including vestibular organ derangement. There are, in addition, several emergency situations wherein radiation becomes an important stress - the occurrence of traumatic injury, temperature and atmosphere control failure, or the occurrence of a clinically significant infectious process.

Independent stresses can combine in one of three ways: (1) additively, where the sum of the single stress effects is equal to the combined effect; (2) synergistically, where the combined effect is greater than the sum of the single effects; and

(3) antagonistically, where the combined effect is less than the sum of the single effects (a protection effect). Unfortunately, it is not possible to make consistently sensible statements regarding this aspect of the different combined stresses, but some comments will be made wherever it seems required.

There has been no carefully controlled or evaluated human experience involving the interaction of radiation injury with the majority of the stresses to be discussed. In addition, the studies involving the whole animal have often been somewhat imprecise. The most useful data in this difficult area, therefore, are those that are derived from cellular systems or that employ genetic end points. Any inferences regarding human responses are, therefore, tenuous but by no means impossible, since radiation injury is best understood and interpreted at the cellular level.

As a further note of introduction, a survey of the literature quickly revealed that life scientists in the U.S.S.R. are devoting considerable attention to selected problems of combined stress - notably those associated with flight dynamics. This is seen in the reports of their earliest unmanned flight studies that carried recoverable biological payload. Their attention is more noticeable in contrast to a seemingly less intense level of interest among U.S. specialists in aerospace medicine and biology.

In summary, combined stresses discussed in this section can be tentatively assigned the types of interactions shown in Table 13. The terms are used as defined in the beginning of this section: Additive means simple summation of effects; synergistic means an interaction that produces a greater than additive effect; antagonistic means an interaction that produces a less than additive effect; and neutral means no detectable effect of the non-radiation stress alone or in combination.

The preponderance of interpretations of apparently synergistic interactions is worth emphasizing, since it does not encourage the design engineer to relax his criteria. A highly stable cabin environment is worth the extra effort to assure long-range mission success. The vibrational and acceleration forces are to some degree manageable through engineering, but at least are brief in their appearance. The ultimate effect of zero gravity still remains the biological enigma.

4.0 DOSIMETRY FOR CHARACTERIZATION OF SPACE RADIATION EXPOSURE

From a physical point of view, the type of radiation, flux density, and energy spectrum completely define the radiation field which produces a biological change. From a biological point of view, however, it is the energy transferred by this field to the biological entity under consideration which is most important. When the physics of interactions between tissues and incident radiations are known, then the physical specification suffices, although in many instances long and complicated computer programs are required to apply such physical knowledge. The most logical choice for space radiation monitoring, in view of the above difficulty, appears to be a tissue-equivalent system. The problems associated with radiation monitoring of a manned space flight must, in other words, be clearly distinguished from the acquisition of geophysical data or of information aimed primarily at computation of shielding requirements. The chief requirement is for an instrument which will field a direct indication of absorbed dose in tissue in real time. Such a requirement rules out instruments which are only capable of measuring flux or even flux plug energy distribution because of the complexity of using such data to provide dosimetric information. The dependence on geometrical variation, angular incidence, self-shielding, lack of accurate physical data on interaction properties between the radiation and tissue, plus the degree of complexity of the computations themselves, tends to rule out this method. It seems reasonable to conclude that knowledge of the physical characteristics of the radiation environment, although it may provide data for other scientific or engineering purposes, is not immediately applicable to radiation monitoring. Such information, therefore, should be gathered and treated separately from the problem of crew safety. For the latter problem, a practical approach to a detector whose atomic composition is as close as possible to that of tissue and whose response is proportional to energy absorbed, rather than to flux density, appears to be the best course to follow, even within the limitations and compromises necessary.

The development of such a system should take two lines of approach. First, a system to supply both rate and total absorbed dose in rads as a function of mission time should be engineered for space vehicle application. Absorbed dose should be determined in such a manner as to supply values at superficial points and at critical depths in the body. Second, a tissue-equivalent system for determining the energy absorbed per event in a representative tissue volume centered at the points where absorbed dose has been measured should be developed on a simplified basis so that energy deposited per event can be classified into several broad LET groups. Total absorbed dose and dose rate should be displayed and weighted in accordance with LET distribution if the situation warrants. Absorbed dose, dose rate in rads, and LET groups should be recorded for future reference.

Dose should obviously then be defined in terms of rads, and preferably it should be measured in a tissue-equivalent system at least three levels, including 0, 5 and possibly 10 cm in equivalent tissue depth. Accuracy of these determinations should be no less than ± 15 percent. If compromise is required, it would then seem that at least two measurements should be made: One at the equivalent level of the skin and a second at about 5 cm, assuming it to be the mean depth of the bone marrow. The spanning measurements suggested above are statistically better but probably would invoke a greater weight penalty and instrument sophistication.

A very important question that has been debated repeatedly concerns the alternative whether the radiation field inside the vehicle should be probed with stationary sensors distributed throughout the ship or whether microsensors on the bodies of the crew members should be given preference. It could be argued in favor of the first alternative that stationary sensors would free the crewman from additional gear in his space suit. Furthermore, such sensors could be of greater weight and bulk, thereby allowing a more elaborate analysis of the local radiation level. In favor of the second alternative, sensors on the body would indicate the radiation level exactly at the location where it counts. It is even conceivable that the differential reading of a pair of sensors on the chest and back would provide a crude measure of depth-dose. The main argument in favor of sensors on the body naturally rests in the advantage that it would cover all contingencies of each individual's activity. In terms of the Lunar Mission, it would require no changes or adjustments whether the individual is in the heavily shielded Apollo Vehicle or in the extremely light Lunar Module, or is engaged in extravehicular activity. To be sure, for the last named condition, it should be recognized that there are very high fluxes of low-energy electrons and protons at many locations in the space environment. These should be detected and measured on the outside of the vehicle prior to any outboard excursion, since they can potentially produce a very high surface tissue dose.

A final question concerns the need of LET sensors as a component of dosimetric instrumentation in space. In discussing the problem, measurement of heavy nuclei is excluded. In its conventional interpretation, LET defines the inhomogeneity in the distribution of the ionization events at the microscopic level. The diameter of the ionization columns which heavy nuclei produce in tissue exceeds the dimensions of a single cell, creating a peculiar exposure pattern with a few cells exposed to very high doses and the surrounding bulk of the cell population remaining entirely unaffected. It seems generally agreed upon that the biological significance of this type of exposure cannot be dealt with adequately in terms of the conventional LET concept. However, it has been shown that (1) it takes enormous doses of radiation delivered through a microbeam 0.025 mm in diameter to cause destruction of the brain cells in the beam path; (2) the epithelial cells of the lens of the eye are quite sensitive to this type of radiation, but the microbeam only disrupts one or two such cells, which is insufficient to cause a cataract; (3) the hair follicles are quite sensitive to this beam, and relatively small doses to the individual hair follicle will ccause the hair from the follicle to turn gray; (4) rapidly proliferating cells such as those of bone marrow or intestinal epithelium certainly present no practical problem, since the very few cells which might be inactivated by heavy particles of interstellar space would be quickly replaced by normal cells; and (5) non-dividing cells such as those of the liver or muscle and like those of the brain may be expected to be very insensitive to this type of radiation. Even if sensitivity were somewhat higher than that of brain cells, loss of a few of these cells would certainly not be serious.

If heavy nuclei are excluded, the LET problem appears only of limited importance for the remaining types of ionizing agents represented in the galactic radiation beam. The two main components of the primary galactic beam (i.e., protons and alpha particles) produce LET values exceeding those of standard x-rays only at energies from a few Mev down to the Bragg peak. These energies are not represented at all in the incident beam. Low-energy protons and alpha particles originate only locally in nuclear disintegrations in absorbing material. It should be remembered at this point that the spectacular multipronged disintegration stars which cosmic-ray primaries release in collisions with silver and bromine nuclei of nuclear emulsions are absent in materials made up of low Z components such as living tissue. The number of prongs per star in these substances is small and the star frequency low; hence, terminating protons and alpha particles contribute only insignificantly to total ionization dose. In fact, the question could be raised whether a QF considerably smaller than unity would not be applicable to the total absorbed dose from the galactic beam. Animal experimentation with protons in the multihundred Mev energy region has consistently yielded RBE factors of 0.6 to unity, depending on the particular reaction studied. These findings are in line with the fact that the local LET spectra of high-energy protons in tissue center about much lower mean LET values than standard x-rays. Since we are excluding heavy nuclei in the present discussion, the remaining ionization dose of the galactic beam is produced mainly by protons of very high energies. The QF smaller than unity that should be applied to the insignificant dose fraction due to terminating protons and alpha particles from disintegration stars in tissue.

The situation is different for the proton and alpha fluxes of solar particle beams. Protons and alpha particles reaching the end of their ionization ranges (so-called "enders") contribute noticeably to the total ionization dose in systems of medium-light shielding (1.5 g/cm^2) and become the predominant contributors to the total dose in the skin and subcutaneous tissue behind low shielding. Under the latter conditions, calculation suggests a QF of 4 to 5 for late effects from combined proton and alpha particle dose to a depth of a few mm. On the other hand, it is not possible to say unequivocally whether these very special conditions would justify the great complications which a separate determination of LET would introduce in dosimetric instrumentation. Since the conditions in question occur only under conditions of low shielding and are always accompanied by a very steep drop in absorbed dose in the first mm, it is possible that measurement of dose in rads with application of a suitable QF factor to the skin dose would suffice.

TABLE 1

ESTIMATED HIGH-INTENSITY RADIATION DOSE LEVELS
FOR PRODUCTION OF EARLY PRODROMAL RESPONSE*

Clinical Sign	Probability of Response		
	10 Percent (rads)**	50 Percent (rads)**	90 Percent (rads)**
Anorexia	40	100	240
Nausea	50	170	320
Vomiting	60	215	380
Diarrhea	90	240	390

*Symptoms appear in less than 1 to 2 hours ($T_{50} \sim 2.5$ hrs) of exposure and subside in less than 1 to 2 days.

**Point of interest for dose estimation: A 15 cm diameter sphere in the mid-epigastric region; QF assumed to be unity.

TABLE 2

ESTIMATED HIGH-INTENSITY RADIATION DOSE LEVELS

FOR PRODUCTION OF HEMATOLOGICAL DEPRESSION*

	Reduction from Normal		
Circulating Element	25 Percent (rads)**	50 Percent (rads)**	75 Percent (rads)**
Platelets***	50	120	250
Lymphocytes***	60	150	300
Neutrophils***	80	190	390

*Symptoms appear within 1 to 10 days after bone marrow exposure.

**Point of interest for dose estimation average depth of 5cm; QF assumed to be unity.

***Nadir ~3, 25, and 30 days, respectively, for lymphocytes, neutrophils, and platelets.

TABLE 3

ESTIMATED HIGH-INTENSITY WHOLE-BODY DOSE LEVELS

FOR PRODUCTION OF HEMATOPOIETIC LETHALITY*

Response Probability Level (percent)	Dose (rads)**
10	220
50	285
90	350

*Symptoms begin within a few hours with the prodromal reaction, followed by progressive hematological depression terminating in death in 2 to 8 weeks.

**Point of interest for dose estimation: 11-cm depth; QF assumed to be unity.

TABLE 4

ESTIMATED DOSES OF HIGH-INTENSITY RADIATION FOR PRODUCTION OF ERYTHEMA AND MOIST DESQUAMATION OF THE SKIN*

Clinical Sign	Probability of Response: 10 Percent (rads)**	50 Percent (rads)**	90 Percent (rads)**
Erythema	400	575	750
Moist Desquamation	1400	2000	2600

*Symptoms appear within a few hours to several days.

**Point of interest for dose estimation 0.1-mm depth; area exposed, 35 to 100 cm^2; QF assumed to be unity. An overall modifying factor (QF_T) weighted for LET should be applied to the dose values given here (see Table 5). An area effectiveness factor of 1.25 is suggested to reduce the dose values given here when exposure involves skin areas up to or greater than 150 cm^2.

TABLE 5

SUGGESTED QF VALUES FOR EARLY RESPONSES TO HIGH-INTENSITY SPACE RADIATION EXPOSURE

Criterion of Effect and Point of Interest	Local LET Component	QF_E**
Skin Responses* (depth of 0.1 mm)	$\leqq$ 3.5 kev/μ $\geqq$ 20. kev/μ	1 3
Prodomal Syndrome (15-cm sphere in epigastrium)	all LET's	1
Hematological Responses (average depth of 5-cm)	all LET's	1
Lethality, Hematological Syndrome (average depth of 5-cm)	all LET's	1
Lethality, Dysenteric Syndrome (10- to 15-cm depth)	$\leqq$ 3.5 kev/μ $\geqq$ 3.5 kev/μ	1 2

*A linear relation between QF and LET may be assumed between these limits.

**To a first approximation

$$QF_E = 0.9 + 0.05\,\bar{L}$$

where $\bar{L}$ is the local mean LET at the anatomical site of interest.

TABLE 6

SUGGESTED DOSE-RATE OR "RATE-EFFECTIVENESS" FACTORS (f_r) FOR EARLY RESPONSES FOLLOWING EXPOSURE TO LOW-LET RADIATIONS

	Duration of Exposure to Produce Same Response Level		
	Skin Erythema and Desquamation	Prodromal Signs	Hematological Depression and Lethality
A. High Dose-Rate			
Duration of Exposure for Maximum Effectiveness	1 - 2 hours or less	2 - 4 hours or less	1 - 2 days or less
B. Low Dose-Rate			
Duration of Exposure for Minimum Effectiveness	4 - 6 days or longer	2 - 4 days or longer	3 - 4 weeks
Ratio of Total Doses to Produce Same Response Level (B/A)	3	2.5	2
Rate-Effectiveness Factor (f_r)	1/3	1/2.5	1/2

TABLE 7

SUGGESTED VALUES OF QF FOR LATE RESPONSES AS A FUNCTION OF AVERAGE LET

LET (kev/μ in water)	QF_L *
X rays and electrons of any LET	1
3.5 or less	1
3.5 - 7	1 - 2
7 - 23	2 - 5
23 - 53	5 - 10
53 - 175	10 - 20

*To a first approximation:

$$QF_L = 0.8 + 0.16\ \bar{L}$$

where $\bar{L}$ is the local mean LET at the anatomical site of interest.

TABLE 8

EXAMPLE OF DOSE-ACCUMULATION RECORD FOR A HYPOTHETICAL ONE-YEAR MISSION

Elapsed Time (days)	Mean Dose Rate (rads/day)	Measured Dose*(D) (rads)	Effect Factor	Estimated Dose**(RES) (reu)	Allowable Dose(RES_m) Remaining (reu)
0	--	--	--	--	250
0 - 1	10	10	1.4	14	236
2 - 150	<1	15	1	15	221
151 - 152	20 - 30	45	2	90	131
153 - 364	<1	20	1	20	111
365	15	15	1.5	23	89
Total		105		162	

*At 5-cm depth; tissue-equivalent.

**QF assumed to be unity.

TABLE 9

EXAMPLES OF EXPOSURE-ACCUMULATION FACTORS OR MULTIPLES OF THE 1-YEAR RES* FOR MISSIONS OF SPECIFIED DURATION

Mission Duration (years)	Multiple
1	1.0
2	1.8
3	2.4
4	2.8
5	3.0

*At 5-cm depth, tissue-equivalent; total-body exposure.

TABLE 10

SUGGESTED ABSORBED DOSES* OF REFERENCE RADIATION FOR PRODUCTION OF LATE CHANGES IN THE OCULAR LENS

Probability of Response	High-Intensity Single (1-day) Dose	Protracted** Dose
	(rads)	(rads)
Minimal ($p \geq 0$)	150	300
Median ($p \cong 0.5$)***	300	600
Maximal ($p \leq 1$)	650	1300

*Point of interest for dose estimation, 3-mm depth.

**Dose protracted over 7 weeks or longer.

***Assuming log-normal distribution of response.

TABLE 11

SUGGESTED ABSORBED DOSES* OF REFERENCE RADIATION FOR PRODUCTION OF LATE SKIN NECROSIS

Probability of Response	High-Intensity Single (1-day) Dose	Fractionated or Protracted Dose
	(rads)	(rads)
10 Percent	2000	4600
50 Percent	2800	6400
90 Percent	3600	8200

*Point of interest for dose estimation, 0.1-mm depth; area exposed $< 150\ cm^2$.

TABLE 12

SUGGESTED REFERENCE RADIATION DOSE-RESPONSE RELATIONSHIPS FOR GENERAL LIFE SHORTENING AND INCREASED INCIDENCE OF LEUKEMIA

Response	High-Intensity Exposure*	Low-Intensity Exposure**
Life Shortening***	~10 days/rad	~ 3 days/rad
Leukemia	2 - $4/10^6$ man-yrs/rad	1 - $2/10^6$ man-yrs/rad

*Assumed to be 50 rads/day and greater.

**Assumed to be 1 rad/day and less.

***Site of interest for dose estimation, 5-cm depth; whole-body exposure.

TABLE 13

SUMMARY OF STRESS COMBINATIONS AND SUSPECTED TYPES OF INTERACTIONS

Combined Stresses	
Radiation-Noise	Neutral to synergistic
Radiation-Hypothermia	Neutral to synergistic
Radiation-Hyperthermia	Neutral to synergistic
Radiation-Hypoxia	Synergistic (antagonistic for only brief periods during exposure)
Radiation-Hyperoxia	Neutral to additive
Radiation-Physiological Factors	Synergistic
Radiation-Emotional Factors	Indeterminate
Radiation-Vibration	Neutral to additive to synergistic
Radiation-Acceleration	Antagonistic to neutral to synergistic
Radiation-Weightlessness	Additive to synergistic
Radiation-Vestibular Factors	Neutral to additive
Radiation-Emergency Situations	Neutral to synergistic
Three-Stress Interactions	Indeterminate

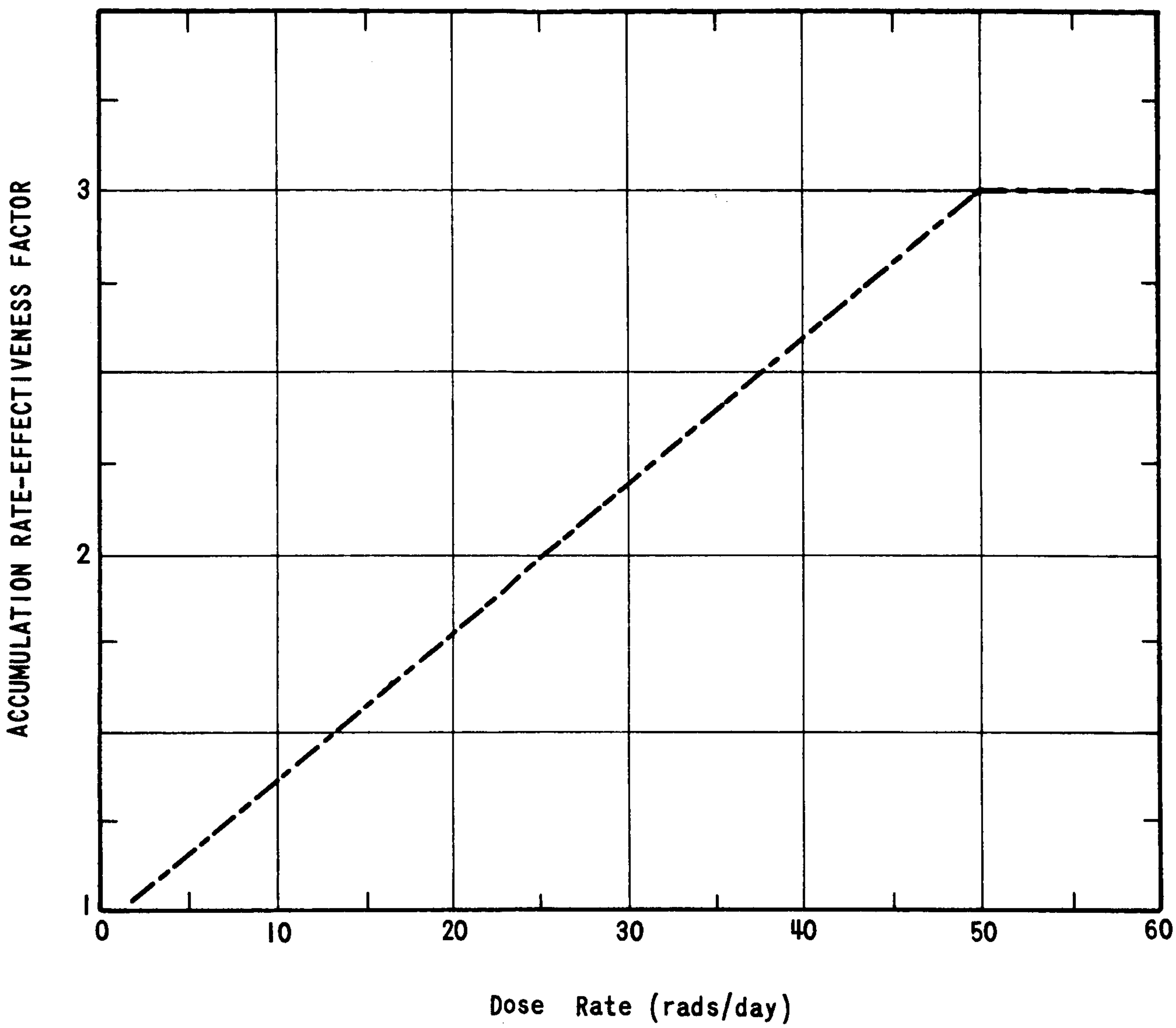

FIGURE 1. ACCUMULATION RATE-EFFECTIVENESS FACTOR (RF_A) FOR PROGRESSIVE BONE MARROW INJURY AS A FUNCTION OF MEAN DAILY DOSE-RATE (TOTAL-BODY EXPOSURE).

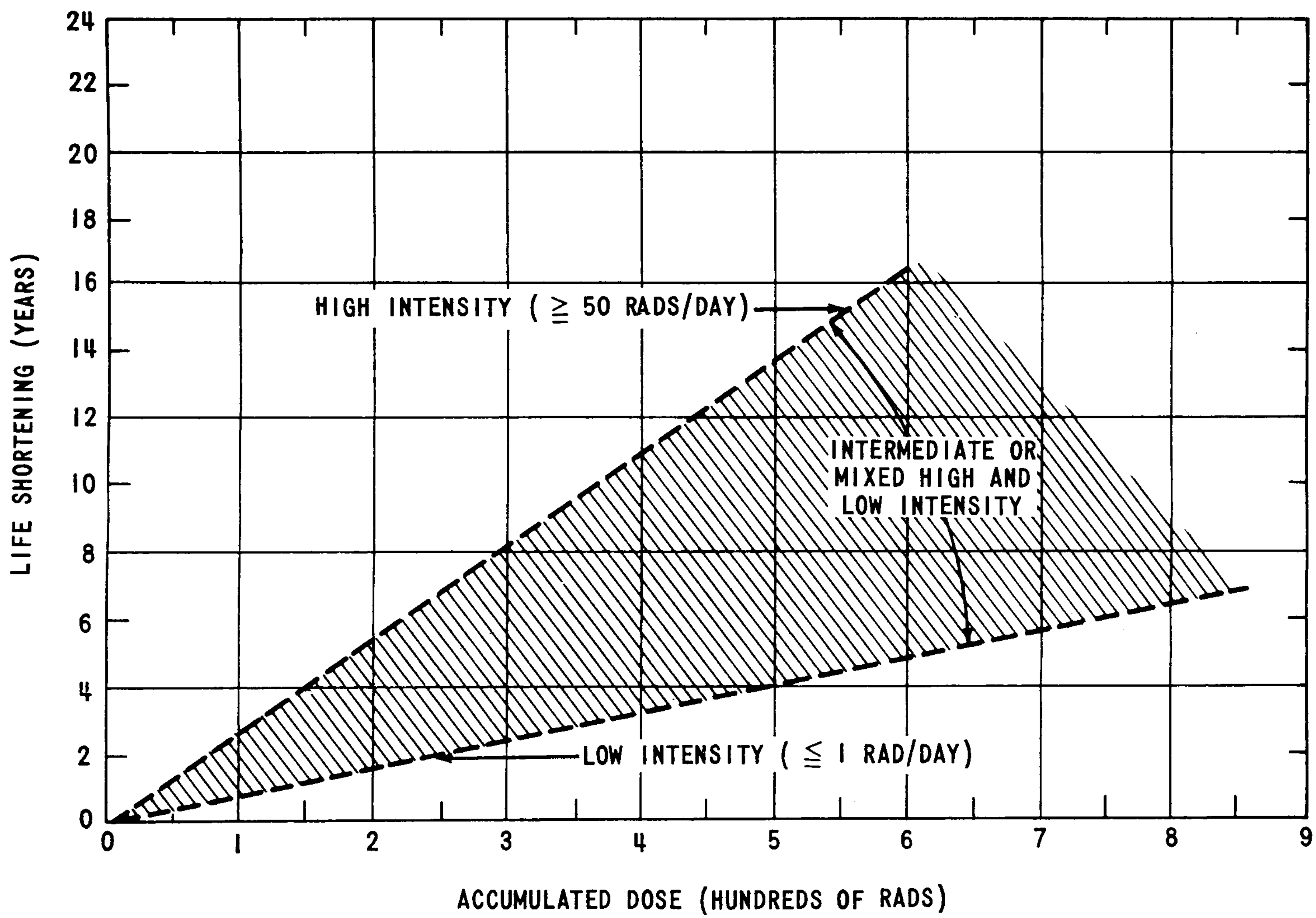

FIGURE 2 - LIFE SHORTENING AS A FUNCTION OF ACCUMULATED DOSE

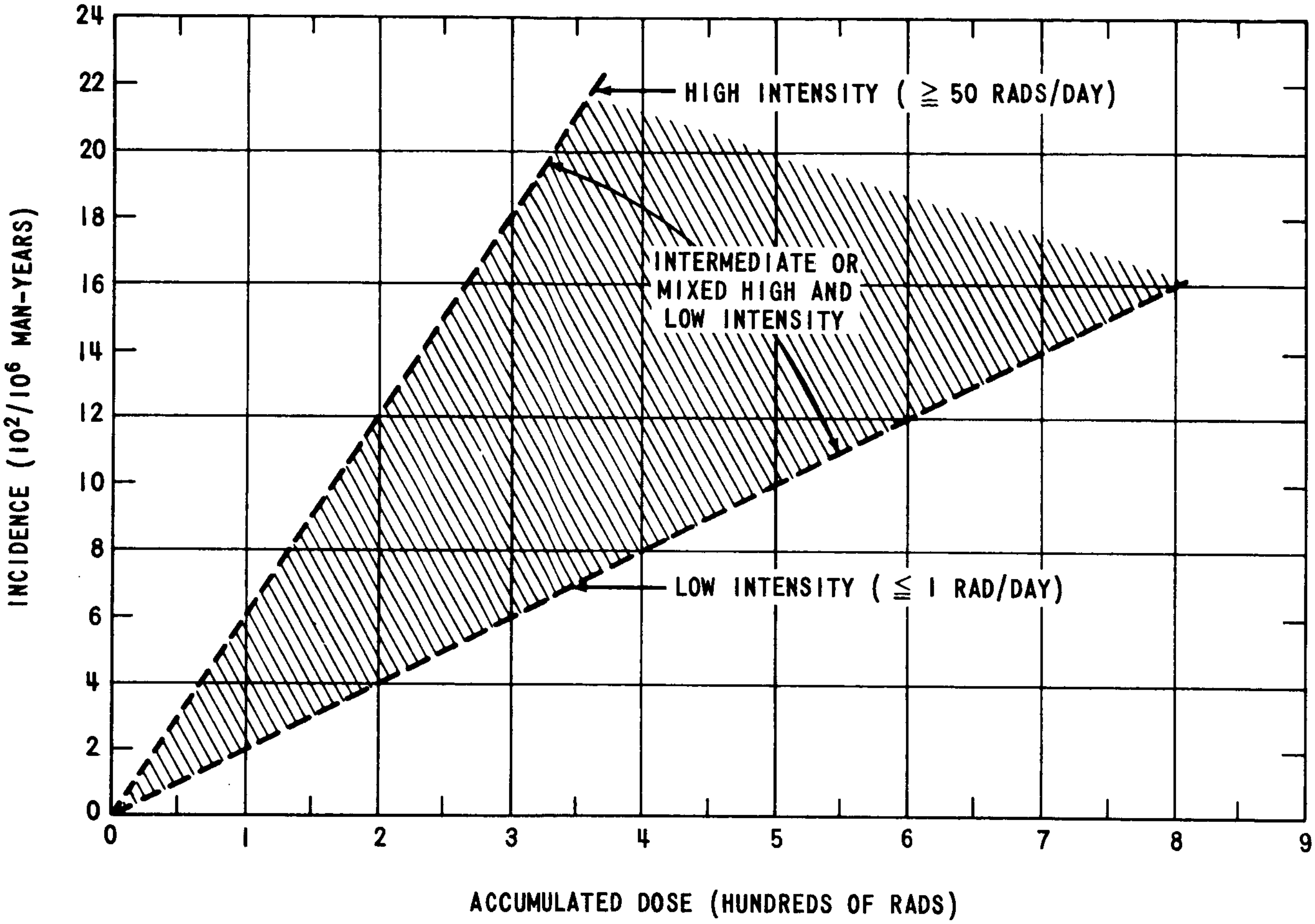

FIGURE 3 - INCREASED INCIDENCE OF LEUKEMIA AS A FUNCTION OF ACCUMULATED DOSE

NONIONIZING RADIATION

STATEMENT OF THE PROBLEM

Nonionizing radiation includes the ultraviolet, visual, infrared, and microwave spectra. Most of the information received by the astronaut is visual and the act of seeing requires the presence of light or luminous energy. This light must be maintained at proper levels and contrasts for effective vision. Light at extremely high levels causes discomfort and at higher levels results in permanent injury to the eyes. Nonionizing radiation encompasses pathological as well as physiological effects. Sources of this radiation are the sun, lasers, and radio frequency emitters such as radar sets. The solar spectrum between 2,000 to 20,000 A° is the region of concern. Lasers are considered since these are potential space communications devices and can cause retinal damage. Microwaves can cause injury through the release of heat in tissues. Only the oculo-visual effects of nonionizing radiations are considered in this discussion.

a. Pathological

(1) Retinal burn. Direct observation of the sun through a clear plastic helmet while in orbital EVA can cause permanent injury to the eyes. Exposure of the eyes for one to two seconds to the solar visual and infrared fluxes will result in a retinal burn in an area

corresponding to the image of the sun. The threshold burn exposure time is less at the fovea or central portion of the eye than in the periphery. Loss of foveal vision results in the inability to read fine print or perform tasks requiring fine detail, however, tasks requiring gross visual capability, such as driving an automobile, could still be performed if only a small area of the retina were damaged. Retinal burn can result from the sun's rays approaching the eye from the side. This is most insidious because there is no pain associated with this injury.

(2) Photokeratitis. Photokeratitis is an actinic pathological process caused by ultraviolet radiation and resulting in an erosion of the outer layers of the cornea. It is a reversible process in the absence of secondary infection. Within several hours after initial exposure the invoked symptoms include severe pain in the eyes and photophobia. An exposed individual can be incapacitated for approximately 24 hours. Outside the atmosphere the threshold exposure time for photokeratitis from solar radiation while wearing only a clear plastic helmet is a little over a minute.

(3) Cataract. Coagulation of the protein of the crystalline lens of the eye or "cataract" is a potential hazard of infrared and microwave radiation. This

injury results in functional blindness. Approximately 40 percent of solar radiation is in the infrared region of the spectrum. Solar radiation in these spectral regions is one third more intense in space than it is at sea level. The onset of cataract varies from several days to months depending upon the type and amount of exposure. Cataracts can be surgically corrected.

b. Physiological

The extreme brightness of the sun outside the atmosphere combined with the sharp contrasts of deep space and shadows present a severe visual problem. The eyes remain adapted to the brightest areas observed. For this reason the dark shadow areas appear blank. Since there is no atmosphere in space to scatter light and provide fill light, all shadows are absolutely black. On the other hand the extreme brightness of the sun causes highly reflective surfaces to "wash out" low contrast visual targets. These targets disappear. Color perception is degraded by the use of filters for eye protection. This color change must be considered in all color evaluations.

PAST MEDICAL APPROACH

The present approach to eye protection from nonionizing electromagnetic radiation is to provide shielding in the form of attenuating filters. This sometimes presents a problem because a filter which provides protection from pathological effects may be too dense to allow normal visual function.

The use of filters which selectively attenuate the dangerous spectral energies yet transmit sufficient luminous energy for adequate vision can eliminate this problem. However, fixed attenuating filters performed satisfactorily during the Gemini EVA missions. Conversely, it is important to note that past missions did not impose as severe conditions on the eyes and vision as the Apollo missions will. Normal skin sunburn cannot occur inside the spacecraft because the window glass attenuates the ultraviolet radiation to acceptable levels.

PRESENT MEDICAL POSITION

Since precise visual function is necessary for spaceflight tasks, exposure of the eyes must be kept below the presently known threshold limits. These are:

a.	Attenuate solar to 10^{-5} transmittance	(2,200 - 3,100 A° Spectrum)
b.	1 cal/cm^2/sec	(4,000 - 7,000 A° Spectrum)
c.	1 cal/cm^2/sec	(7,800 A° - 60,000 A° Spectrum)
d.	10 milliwatts/cm^2 continuous	(microwave radiation)

FUTURE EFFORTS

Efforts to explore visual function in the region just below retinal burn threshold in the flashblindness-glare zone are required for specifying ophthalmic filter density. The development of a practical self-attenuating ophthalmic filter would be the single most important contribution to eye protection from luminous radiations. Considerable effort has been expended fruitlessly in this area in the past. This work will be followed if not directly funded by NASA. Selective dichroic filters will be developed for special visual requirements as they arise. Efforts to solve the problem of fill light for shadows will be pursued. Chemical flares and special reflectors may provide adequate shadow lighting. Each phase of future mission profiles for marginal visual tasks and eye hazards must be evaluated. Early discovery of the visual/eye problems to be encountered will permit timely solution of these problems with least cost to the program and the astronauts.

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METEOROIDS

STATEMENT OF THE PROBLEM

Experiments with hypervelocity projectiles penetrating typical spacecraft structures have shown that the following potential hazards exist:

Blast

The injurious effects of blast arise from the rate and magnitude of pressure rise, the impulse duration, and the rate of pressure fall. Injury to man is less likely to occur if the overpressure is of short duration and the pressure rise is slow. Additionally, the damage is most severe where tissue density variations are greatest. A blast wave striking the body produces within it a shock wave that passes from one layer of tissue to another. At the interfaces between high density and lower density tissues, the shock wave is reflected producing local tension in the denser medium.

Shock waves traveling through a medium containing small gas bubbles can be particularly damaging. The bubbles being a compressive component, implode generating high local pressures. Rapid re-expansion of these bubbles produces new shock waves which emanate radially from the bubbles. This phenomenon is responsible for damage to the air containing portions of the lungs. The LD_{50} for man is 57 psi reflected pressure or 235 psi incident pressure for pulses of one to three millisecond duration. Desaga found in his work that the lethal amount of overpressure for dogs and man is nearly equal and Richmond in experiments with dogs found LD_{50} values for 400 milliseconds of 48 psi incident pressure.

Burns

The effects of direct skin contact with flame are well known and have been studied extensively. These studies indicate that the magnitude of the injury depends upon the combinations of skin surface temperature and exposure time. For example, a skin surface temperature of 70°C will kill all epidermal cells (minimal second degree burn) in one second.

Flashblindness

During penetration considerable optical radiation (about 1,000 watts per steradian) is produced and can last for a few milliseconds after wall failure. However, such radiation does not seem to constitute a hazard.

Penetrating Wounds

Material fragments produced by impact can penetrate tissues and cause flesh wounds. The magnitude of such injury depends upon the impact energy, the nature and size of projectile and the type and configuration of the wall material.

Toxic Products

A high temperature flash is produced during meteoroid penetration. Depending upon the materials in which energy exchanges occur, gaseous toxic contaminants can be released.

Decompression

The rate of decompression depends on the volume of the container. In general the time interval t in seconds required for an initial pressure P_o to reduce to a given level P (assuming T≈300°K and an adiabatic decompression mode) can be estimated from

$$t = 4 \times 10^{-3} W^{1/2} \frac{V}{A} \left\{ \left(\frac{P_o}{P} \right)^{0.148} - 1 \right\}$$

where V is the free volume of the space cabin in M^3, A is the area responsible for the leak in M^2 and W is the molecular weight of the excaping gas. In the case of a multiple gas atmosphere, the molecular weight of the mixture is

$$W = \frac{\sum W_i N_i}{\sum N_i}$$

where N_i is the concentration of the ith species.

Penetrations large enough to produce explosive decompression can affect crew safety. However, studies with monkeys have indicated that exposure to sudden decompression need not be necessarily fatal if immediate repressurization can be achieved. Whether such repressurization is possible or whether the crew can initiate such operation is not presently known.

PAST MEDICAL APPROACH

In all missions to date prevention of hazards was assured by providing adequate shielding to lower the probability of meteoroid penetration.

PRESENT MEDICAL POSITION

The probability of spacecraft penetration by a hypervelocity particle must be kept below 0.01. Figure 1 shows the pressure vessel wall thickness as a function of mission duration required to achieve this low penetration probability in near-Earth space.

FUTURE EFFORTS

Continued studies to define the material and asteroidal environment throughout the solar system are required. Additionally, methods of increasing shielding effectiveness with minimum weight penalties should be studied. From a medical standpoint present methods of treatment for penetration type injuries should be refined and effective emergency operational procedures for crew protection should be developed. Hazard detection and warning systems, personal protective devices, damage repair techniques and sealing operations should also be given adequate attention.

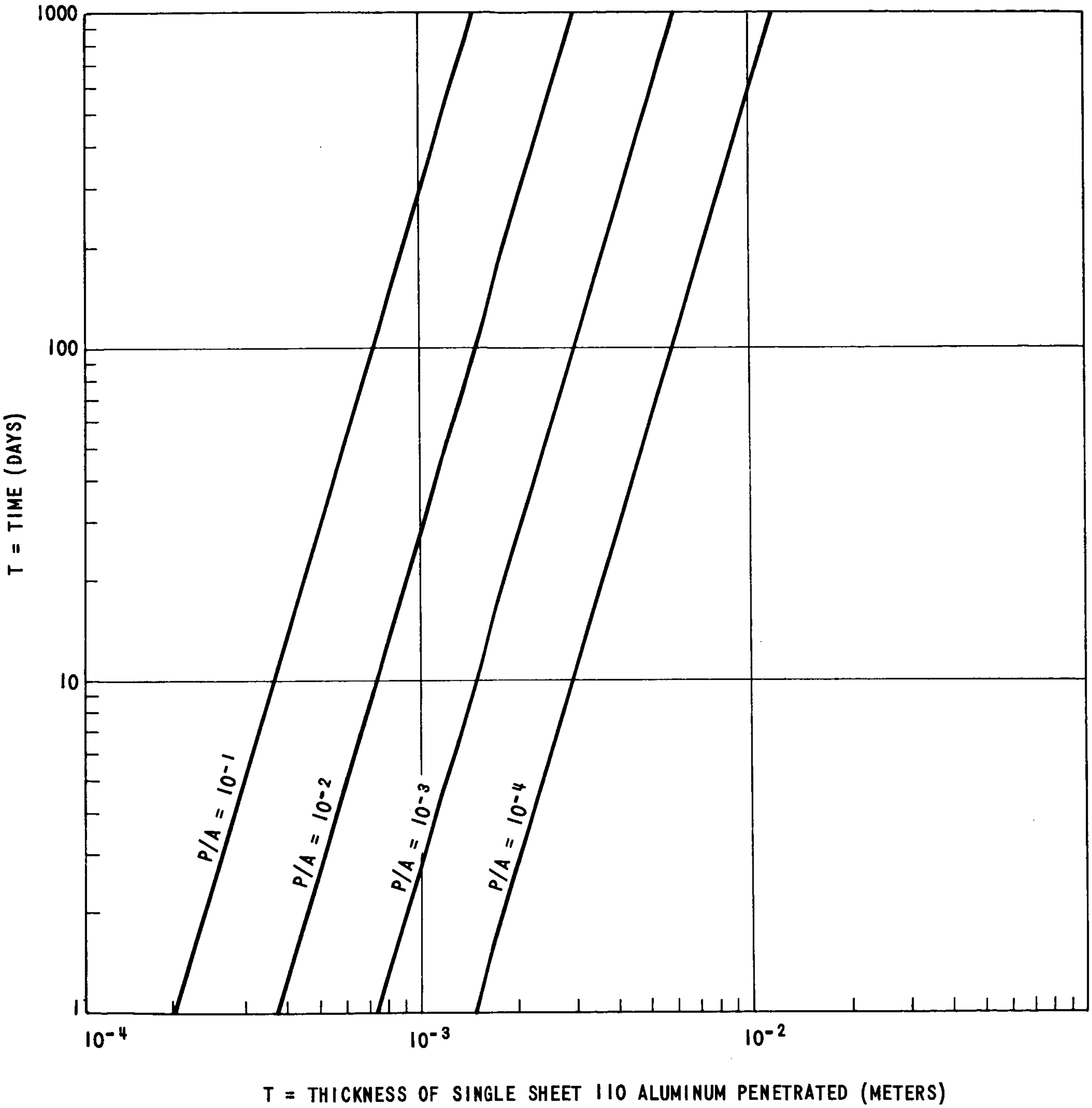

FIGURE 1 - PROBABILITY PER UNIT AREA (m^2) FOR ONE OR MORE METEOROID PENETRATIONS FOR MISSIONS OF VARIOUS DURATION AND WALLS OF VARYING THICKNESS

ALTERED PERIODICITIES

STATEMENT OF THE PROBLEM

Many biological processes of living organisms are periodic in nature. The most well known of these are the circadian (daily) rhythms of sleep, body temperature, flower petal movements, etc., but there are many other biological oscillatory frequencies as well. These rhythms are believed to be evolutionary in origin, and responsive to terrestrial cues such as light/dark cycles. During manned space travel beyond his evolutionary environment, temporal factors will have to be included as part of the provided environment to avoid breakdown of periodicities. Although work/rest schedules may be the governing input, there are basic biological questions related to circadian rhythms which may be of importance.

It is possible to divide circadian rhythm research into four categories: (1) the occurrence and general characteristics, (2) environmental phase-setting, (3) the basic mechanism, and (4) the importance of these rhythms to the organism. The first two aspects have been thoroughly studied and can be found in several excellent reviews (1, 2, 3, 4, and 5).

These may be summarized briefly by saying: (1) from unicellular organisms to man there are few biological processes which do not demonstrate periodicity, and (2) circadian processes have a labile temporal relationship with the environment and can be phase-set (entrained) with appropriate light or temperature stimuli.

The latter two aspects, however, have evaded scientific inquiry, although many investigators are attmpting to determine the mechanism of circadian rhythms and the physiological consequence of their disruption (6).

Circadian rhythms, rather than being direct biological responses to the immediate temporal environment may serve a more basic role in the functioning of living systems. Processes must occur not only at the proper place and in sufficient quantity, but must also occur at the proper time. Thus, the circadian mechanism permits interval synchronization of an organism's processes and at the same time synchronizes the total organism to its environment.

A review of the literature on human circadian rhythms shows over 50 physiological variables with significant circadian variations (7). Although this variation is only a small percentage of the total change for a function such as vital capacity it accounts for the majority of the variation in others such as electrolyte excretion. The circadian changes observed are often caused by variations in other processes. Thus, it is not always possible to determine the direct relationship between the observed rhythm and the basic causal mechanism.

Changes circadian rhythms may occur during certain pathological conditions (8, 1, 10, 11). In addition there may be decreased psychological performance associated with changes (dysrhythmia or desynchronization) in circadian rhythms (12, 13). This phenomena is becoming a well known effect of rapid travel across several time zones.

A basic concern of the flight physician and research physiologist in how the human or living organism responds and adapts to the altered environment encountered during space flight. They are interested in how homeostasis is maintained in an environment which has unique properties such as weightlessness, yet which also includes some normal environmental stimuli. Experimental protocols should be designed to determine the magnitude of circadian variation in measurements that are being recorded. If the changes are significant, the recording and analysis should permit their accurate description when evaluating physiological adaptation to long term missions.

If any inflight circadian dysrhythmia occurs, psychological performance levels should be monitored to determine whether the slight decrements noted in ground-based studies become more significant during long duration space flights.

There are two theories regarding the basic mechanism of circadian rhythms: (1) they are the result of a completely endogenous mechanism (biochemical or biophysical oscillator) with other environmental factors, such as light or temperature, acting as phase-setters; and (2) they represent an organism's response to subtle geophysical fluctuations (such as magnetic fields) with light and temperature again acting as phase-setters between the basic mechanism and the environment.

The majority of investigations subscribe to the first theory; however, the required critical evidence has not been collected. Space flight offers an environment in which the two hyptheses can be tested, since during orbital flight the geophysical variations are no longer available to the organism on a 24-hour basis,and during interplanetary flight they should be completely absent or greatly distorted.

At present, there is only suggestive evidence of detrimental effects due to disruption of normal rhythms in abnormal temporal environments. To date, it has not been possible to completely abolish circadian rhythms, only to perturb them. If the second hypothesis proves to be true, a completely new factor will have to be considered during long duration flights, i.e., the lack of a basic temporal co-ordination mechanism.

PAST MEDICAL APPROACH

The basic concern during the Gemini program regarding daily rhythms has been to provide a suitable work/rest schedule for adequate sleep. After some sleep problems were observed, an approximate 24-hour day was instituted. To prepare for the longer flights the astronauts begin to follow this schedule approximately 1 week prior to lift-off.

The Mercury and Gemini medical programs were not designed to pursue basic investigations of biological rhythms. The only inflight data available in sufficient quantity for analysis is the heart rate collected for safety monitoring purposes. Since this is greatly influenced by activity patterns and othe factors unrelated to a basic circadian rhythm, the information which can be obtained is of limited value. However, some changes in daily heart rate rhythms were observed (14).

In addition, EKG parameters were measured during the 14-day GT-7 flight and have been analyszed for circadian periodicities. Although significant changes were detected in several of the parameters, it is impossible to determine at the present time the causes of these changes. The difficulty in interpretation is a result of the lack of previous research dealing with normal ranges of circadian variation in these parameters.

PRESENT MEDICAL POSITION

The crew should sleep simultaneously and operate on a Cape Kennedy day-night schedule as nearly as possible.

FUTURE EFFORTS

In order to evaluate adequately the problems posed regarding circadian rhythms and long term space flight, the following efforts will be started or continued:

1. Review of scientific literature for circadian influences on physiological, psychological, and biochemical processes.

2. Ground-based studies evaluating circadian variations in variables proposed for inflight measurements.

3. Development of analytical procedures for quantitating rhythms in biological processes.

4. Evaluation of all available inflight data (human and animal) for changes in normal periodic patterns.

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MAGNETIC FIELDS

STATEMENT OF THE PROBLEM

Interplanetary magnetic fields and those about the Moon, Mars and Venus are small in intensity relative to the geomagnetic field. Consequently, lunar and interplanetary missions will expose astronauts to abnormally low natural magnetic fields. Present knowledge of interplanetary and planetary magnetic field conditions are based on a limited number of U. S. and USSR measurements by deep space probes. On the basis of these measurements it is now known that at a distance of 10 to 13 earth radii from the surface of the earth, the geomagnetic field gradually merges with the solar magnetic field. At earth distances the solar field has a normal intensity of a few gamma.* However, following violent solar activity this normal field intensity may increase by as much as a factor of 10.

In contrast to the absence of natural magnetic fields in deep space, possible future techniques of radiation protection using magnetic fields, and advanced electromagnetic propulsion systems may yield local spacecraft magnetic fields of much greater intensity than that encountered on the Earth. If assessment of

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*One gamma is equal to 10^{-5} gauss.

the response of man, both physiological and psychological, indicates such exposure to be harmful, it will be necessary to provide shielding in the vehicle to protect the astronaut from such exposure.

PAST MEDICAL APPROACH

Biomagnetic studies have not yet extended over a broad spectrum of magnetic field strengths. Additionally, systematic physiological studies on the effects of magnetic fields on man is lacking. Available information is primarily based on: (a) incidental observations reported in the literature, and (b) a survey of accidental human exposure while working around powerful magnets used in nuclear physics.

Effects of Low Intensity Magnetic Fields

It is not presently known whether or not the human body through evolution has become dependent on the geomagnetic field for the maintenance of its normal functional integrity. From the few reported studies in which man was exposed to extremely low magnetic fields, one cannot determine if prolonged exposure to such fields could lead to impairment of health or performance. Assessment of individuals exposed continuously for ten days to magnetic field intensities of less than 100 gammas does not indicate that physiological or psychological effects are possible during the nominal Apollo lunar mission. However, careful physiological and psychological observations first on higher primates, then on human subjects exposed to low intensity fields for prolonged periods of time need be conducted before this conclusion can be extended to prolonged non-orbital flights.

Effects of High Intensity Magnetic Fields

Most biomagnetic research upon the effects of high intensity magnetic fields has been carried out on subhuman species and at the cellular level. This provides very little information that specifically applies to exposures of astronauts to high magnetic fields. The use of inordinately high fields often for very short durations does not permit extrapolation of experimental results utilizing large mammals to a possible astronaut situation. Additionally, the experimental situation frequently included fixation of body parts in the magnetic fields as opposed to an actual operational situation where the astronaut would be free to move in the field.

Inconsistent findings in apparently similar experiments undertaken by various investigators make it difficult to define the effects of high magnetic fields. In addition, no one theory proposed to explain and predict the effects of magnetic fields on biological material has been supported by sound empirical evidence. On the basis of the best information presently available, it appears that exposure to magnetic fields of 20,000 gauss (over four orders of magnitude the nominal strength of the geomagnetic field) can be tolerated for short periods. However, it is not certain what magnetic field intensities can be withstood by man during prolonged exposure.

PRESENT MEDICAL POSITION

Review of the available literature on the subject of magnetic field exposures demonstrates that today many varied views exist concerning the significance of the potential hazard to man.* Clearly the present level of knowledge is insufficient to allow confident establishment of acceptable limits. In general, it would appear desirable to limit high intensity exposure to less than 5,000 gauss, although high magnetic fields can be controlled easily so that astronaut exposure could be minimized. On the other hand, reduced magnetic field intensities will be more difficult to cope with. Presently, there is no convincing data indicating the necessity to establish a lower limit of magnetic field strength to which man can be safely exposed.

FUTURE EFFORTS

Assessment of subhuman organisms and human test subjects exposed to magnetic field intensities less than 10^{-3} gauss should continue with emphasis placed upon the implications of man during prolonged space flight.

Results of animal experiments to date have not permitted immediate conclusions that would be helpful in determining effects of magnetic fields on man. Results have not been

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*Busby, D. E., Biomagnetics, NASA CR-889, Washington, D. C., 1967.

sufficiently reproducible or reliable. However, carefully planned studies of higher primates exposed for prolonged periods of time would be appropriate. The information from animal studies would augment systematic whole body exposure of human subjects to magnetic fields of well defined characteristics. Careful physiological and psychological testing of the subjects during and after exposure will furnish valuable data on human tolerance to magnetic fields.

Living organisms demonstrate cyclic phenomenon with periods closely approximating the major geophysical cycles (circadian and lunar month), even in the total absence of environmental cues such as light, temperature, and barometric pressure.* This suggests that biological rhythms may be dependent for their timing on rhythmic changes in the earth's magnetic intensity. Observations made during exposure to highly reduced magnetic fields during extended periods of flight will provide increased understanding of biomagnetic influence upon physiological and psychological function.

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*See Section on altered periodicities.

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EXTRATERRESTRIAL LIFE

STATEMENT OF THE PROBLEM

Scientists are concerned with extraterrestrial life for two reasons. First, contamination of a planet or the moon with terrestrial organisms could result in the permanent loss of a unique opportunity to study life which arose and evolved in a separate planet. Second, exotic life introduced into the Earth's biosphere by returning space vehicles could threaten man and his environment.

Orbital spacecraft could contact extraterrestrial life forms without touching the ground but this is highly improbable unless life spores are present everywhere. No evidence of this eventuality has been found in investigations of the outer atmosphere of Earth. As a safeguard, provision should be made to permit the astronauts to sample the environment external to the spacecraft for viable microbial particles. This experiment could be designed to utilize on-board culturing instruments that hopefully will be in all spacecraft by this time. Provision will be made to permit distinguishing microorganisms indigenous to the spacecraft and the astronauts from those of extra-terrestrial origin.

In addition, contamination of a planet could occur without spacecraft contact with the planet because of current waste management procedures which utilize overboard dumps of spacecraft wastes.

As manned missions approach the gravitational fields of extraterrestrial bodies, these procedures in combination with other practices such as EVA could completely defeat all attempts by unmanned missions to prevent forward contamination.

In landing missions both contamination of the planet, and of the terrestrial biosphere via the returned spacecraft, crew, and samples are distinct possibilities. Sterile procedures are being developed to diminish the probabilities of both types of contamination.

PAST MEDICAL APPROACH

Earth orbital missions were not affected by extra-terrestrial life considerations. Lunar landing missions are constrained by sterility guidelines to avoid lunar contamination. An elaborate scheme which includes a quarantined laboratory for receiving the returned crew and samples of the moon has been developed (Ref. 1-4).

PRESENT MEDICAL POSITION

All possible practical provisions must be made to protect earth's ecology from possible contamination by extra-terrestrial substance that may be infections, toxic, or otherwise harmful to man, animals, and plants.

FUTURE EFFORTS

Methods of sterile sampling, sample isolation, storage, and initial testing must be developed for handling samples obtained from the planets. Sterilization criteria based on realistic expectations of planetary contamination must be evolved.

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MECHANICAL FORCES

The mechanical forces which may be encountered in space flight include both structurally-transmitted and gas-transmitted forces. The significant structurally-transmitted forces are prolonged acceleration, vibration, impact and rotation; the gas-transmitted forces are noise and blast. Excessive exposure to these mechanical forces can have serious medical effects, such as (a) degradation of the crew's abilities to adequately perform their tasks, (b) interference with their normal physiological functioning, or (c) physical damage to their soft body tissues and skeletal structure. Thus, it is necessary to limit the magnitude of these forces so that such undesired results do not occur.

From an engineering standpoint, however, all known methods of limiting these forces impose spacecraft weight penalties. It is, therefore, necessary to establish reasonable levels to which the crew may be exposed and thereby reduce the weight penalties to a minimum. Consequently, we must gain more information on man's performance and tolerance limits, so that engineering personnel can design efficient spacecraft which are within acceptable psychophysiological limits.

Mechanical forces affect different body systems or functions, as shown in the accompanying table.

Force	Body System or Function Affected
Linear Acceleration	Otolith organs and cardiovascular system
Vibration	Eyes, viscera, lungs
Impact	Tissue and skeletal structure
Rotation*	Vestibular systems
Noise and Blast	Hearing, equilibrium, soft body tissues

Because of the diversity of systems and functions affected, the corresponding investigative and corrective approaches differ enough that these cannot be satisfactorily treated as a single topic, despite the similarities in the mechanical nature of the forces involved. Consequently, each of these environmental factors will be discussed individually.

*This is discussed in the "Artificial Gravity" section.

MECHANICAL FORCES - LINEAR ACCELERATION

STATEMENT OF THE PROBLEM

In space flight, linear accelerations are experienced primarily during the launch and re-entry phases, when orbital or escape velocities are attained or dissipated. Such accelerations shift body fluids in a direction opposite to that of the applied force. The resultant physiological effects depend primarily upon the duration and direction of the applied force with respect to the body. When the direction of accelerative force is from head to feet, blood tends to be drained from the eyes and brain and the cardiovascular system must work to overcome the increased hydrostatic pressure. These conditions can progressively produce narrowing of peripheral vision, greyout, blackout, and unconsciousness. Such accelerative effects were first experienced in high speed aircraft performing steeply banked turns and pullouts from dives.

In the supine position the pulmonary blood flow tends to be diverted to the dorsal parts of the lungs. When the arterial blood pressure cannot counteract the pressure gradient produced by transverse accelerative forces, the lungs are no longer fully effective in transferring oxygen into the blood and a blood-oxygen deficiency develops. This deficiency increases with the magnitude and duration of the acceleration until performance is impaired and a hazardous hypoxic condition (oxygen starvation) is reached. The acceptable physiological limits for acceleration magnitudes and durations must therefore be known so the spacecraft may be designed and operated within them. These limits can be satisfactorily determined by ground based centrifuge studies.

Linear accelerations under impoverished visual surroundings also produce illusions of body tilt which aviators must be trained to suppress. The retention of such learned suppression, however, has not been determined for long duration space flight.

PAST MEDICAL APPROACH

Centrifuge simulations of launch and re-entry acceleration profiles were made during the design phases of the orbital Mercury and Gemini programs. These studies established that an essentially supine body position with respect to the launch and re-entry force vectors is necessary to minimize their effects. They also showed that accelerative forces of 6-8 g's were operationally acceptable and that the re-entry phase imposed the limiting stress. Apollo provides a limited lifting capability which can be used to control the maximum re-entry forces within tolerable limits. The launch phase is not considered limiting because of the stepwise saw-tooth acceleration profile that results from booster staging into orbit. Re-oxygenation of the blood can occur during these intervals.

PRESENT MEDICAL POSITION

Studies to date have emphasized the decelerative profile anticipated during return from lunar missions at re-entry velocities of about 37,000 feet per second. Figure 1 summarizes the major effects of linear accelerative forces.

Planetary mission trajectory calculations indicate that re-entry velocities between 55,000 to 65,000 feet per second will be attained; thus the energy that must be absorbed at such velocities will be approximately 2 1/2 times that of a lunar re-entry. The duration of the re-entry will be correspondingly increased. Consequently, the available data is not adequate for missions beyond the moon.

The psychophysiological effects of the increased re-entry duration are not known. Likewise, the effects of the extended zero-g exposure on re-entry tolerance and the post-flight return to earth gravity conditions are not known. Extrapolation of the presently available data is not acceptable and additional studies are required.

FUTURE EFFORTS

Before manned missions beyond the moon are undertaken, a research program should be conducted to establish psychophysiologically acceptable re-entry acceleration values. This program should be conducted in conjunction with planned cardiovascular and vestibular inflight studies in order to fully understand the implications of prolonged weightlessness on re-entry stress responses.

Centrifuge acceleration studies simulating the anticipated re-entry profiles must be conducted with astronaut-type subjects, appropriately deconditioned so as to simulate the influence of exposure to prolonged weightlessness. The profiles should begin with the smallest acceleration acceptable from a spacecraft design standpoint and increase incrementally until performance or physiological limits are determined, or until the centrifuge run is equivalent to a velocity change of 65,000 fps. The angle between the couch back and the re-entry force vector during these simulations should cover a range of potential spacecraft design values. During the simulations the subjects should perform control tasks equivalent to the re-entry tasks and the effectiveness of their performance should be evaluated. A time history of the blood-oxygen concentration should be recorded for each run and, if possible, an objective measurement of the fatigue should also be obtained. If the fatigue cannot be measured objectively, then a subjective evaluation should be provided.

These results, combined with human heat tolerance, spacecraft re-entry acceleration, aerodynamic heating and heat shield heat transmission data will provide the information needed during the spacecraft design to arrive at the best compromise re-entry trajectories.

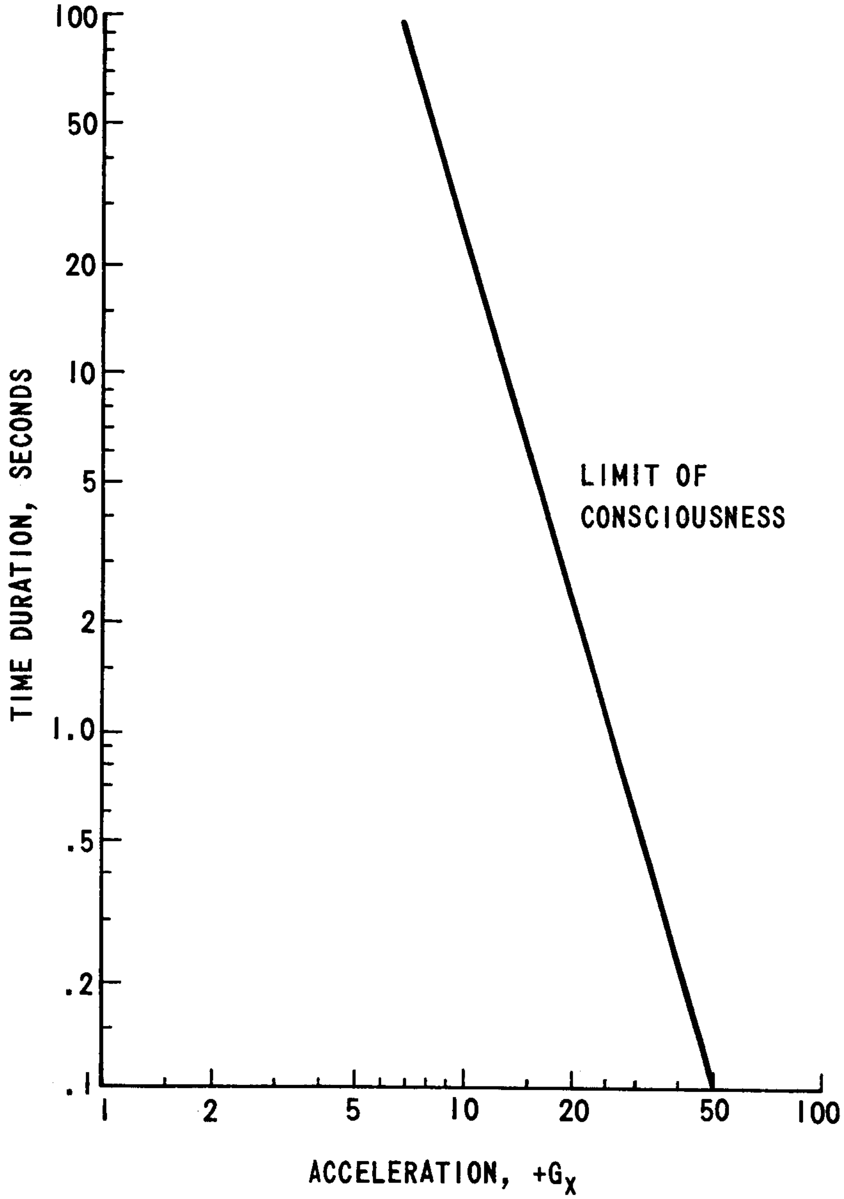


FIGURE I - TOLERANCE OF MAN TO TRANSVERSE ($+G_X$) ACCELERATION

MECHANICAL FORCES - VIBRATION

STATEMENT OF THE PROBLEM

During space flight excessive vibrations can result from the operation of the rocket engines, the vibration of onboard machinery, or aerodynamic buffeting and instability. As with impact and acceleration, the direction of the vibration with respect to the body, and its intensity and duration are important variables. The relationship of the frequencies of vibration to the natural frequencies of various human body systems is also a very important variable because resonance effects can impose much larger stresses than nonsynchronous vibrations.

Degradation of the crew's abilities to perform control tasks under vibration is the most significant aspect of the problem. Such degradation may be aggravated by the supine body position, which is required for support during launch and re-entry phases but which places many parts of the skeletal structure, particularly the head, in almost direct contact with the vibrating structure.

In addition, emergency abort circumstances can lead to aerodynamic instability of the spacecraft and this can expose the crew to potentially injurious oscillating forces.

The detrimental effects of vibration can be controlled by keeping the forces transmitted to the individual below his performance or tolerance limits. This can be achieved by a design which attenuates the vibration at its source or by cushioning the crew. Control of the vibration problem requires that adequate vibration performance and tolerance limits be available during the initial design stages.

PAST MEDICAL APPROACH

Vibration as a manned spacecraft problem was first encountered during Astronaut Shepard's flight (MR-3, May 5, 1961) when he reported a transient period during which the instrument panel readings appeared blurred. Data from an unmanned Gemini test flight also indicated a potential vibration problem. The source was identified as booster rocket fuel system resonance and this was eliminated through redesign. The problem, however, emphasized the incompleteness of performance data for supine crewmen exposed to vibration and a research program including a "sixmode" shake table was initiated with the USAF, Aerospace Medical Research Laboratories, Wright-Patterson AF Base under the direction of Dr. Henning von Gierke.

PRESENT MEDICAL POSITION

Most vibration studies have examined stresses imposed in operating positions found in conventional aircraft and industrial situations; they have therefore emphasized effects in the seated position. Space experience and supporting research have emphasized the semi-supine position and investigated the effects of single and compound vibrations. Some studies of performance of basic visual and manual tasks under X, Y, and Z axis vibrations have been made to evaluate the capabilities of the crews to perform their launch tasks under such conditions. The frequencies have been largely in the sub-sonic range (1-20 cps). Relatively little information exists in the important areas of the combined effects of vibration and acceleration stresses on crew capabilities to perform visual, verbal and manual tasks. Experience to date has indicated that individual performance and tolerance levels may be improved with familiarization and training. Available data on tolerance and performance limits are summarized in Table 1 and Figures 1 and 2.

FUTURE EFFORTS

Additional information on the physiological and performance effects of vibration is obviously needed. The necessary program should include two phases:

Phase 1:

Obtain data on the crew's performance and tolerance for various combinations of vibration and linear acceleration, with representative displays, controls, and tasks.

The crew study phase should include the following parts:

a. Determine performance limits for the use of visual displays and for manual tracking tasks and other control actions. These should be evaluated under a range of vibration frequencies, amplitudes, and super-imposed prolonged accelerations sufficient to cover the conditions that may be encountered during the next ten years.

b. Determine the effects of simulated prolonged weightlessness on tolerance limits under similar combinations of vibration and prolonged acceleration. Both nominal and off-nominal re-entry profiles should be studied, including the fairly large amplitudes that could result from an unstable spacecraft. These combinations may include a steady acceleration with lateral oscillations superimposed.

c. Determine the correlations of performance and tolerance data obtained in the earth's gravity field with actual space flight experience.

Phase 2:

Obtain vibration data on the spacecraft to validate that the environment encountered will be within the crew performance and tolerance limits.

The spacecraft vibration data can be obtained in several successive steps:

a. Static test stand firings of the booster rocket assembly combinations will measure the booster vibration frequencies, for comparison with performance tolerance limits.

b. Shake table tests of assembled modules will indicate the transmissability characteristics of various parts of the entire space vehicle, and provide more refined vibration data.

c. Full scale unmanned flight tests will provide crew couch vibration data that can be compared to the performance or tolerance data to verify their acceptability.

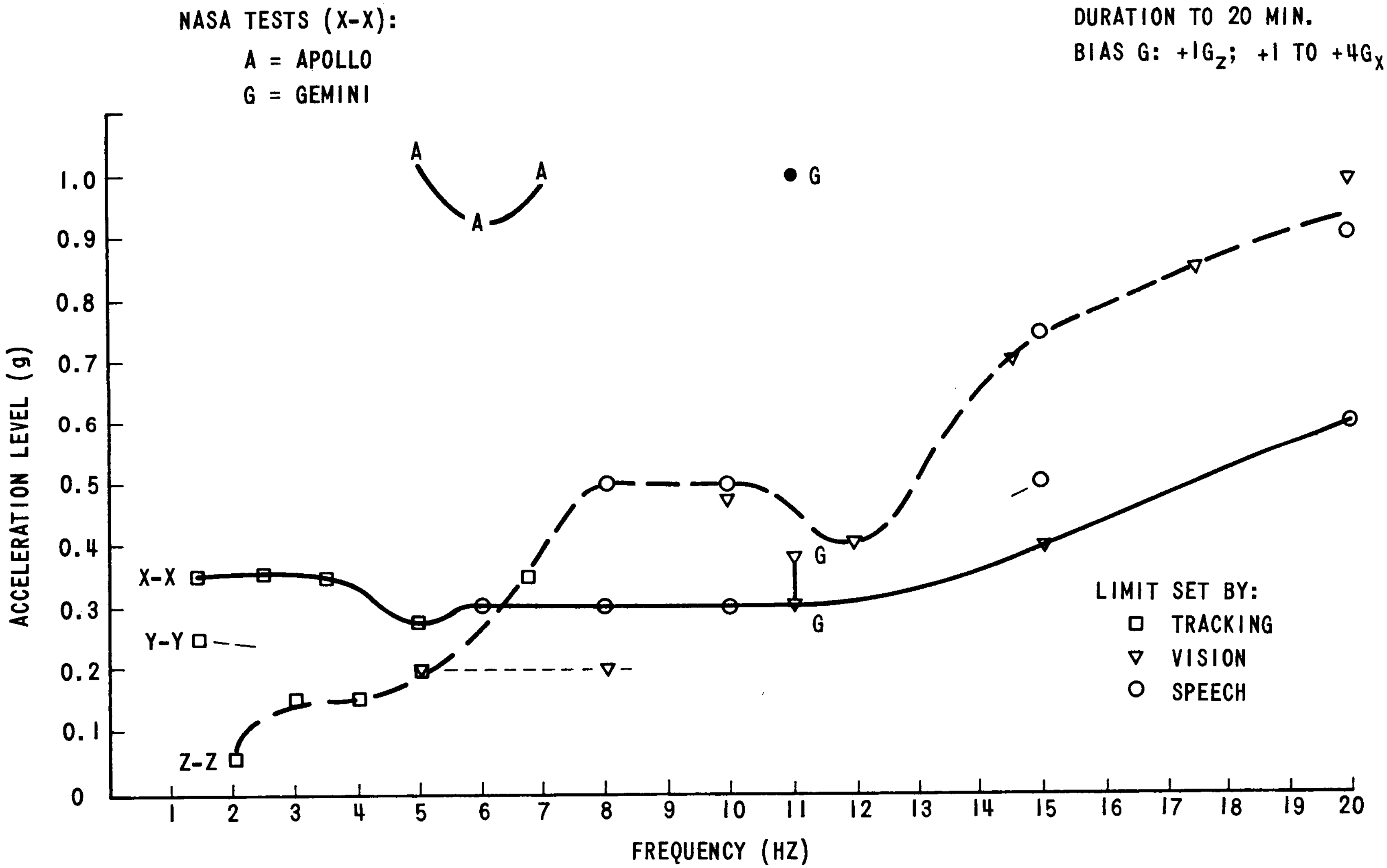
TABLE I

RESONANCES OF HUMAN BODY -SEMI SUPINE

BETWEEN 1-2 CPS BODY GENERALLY RESPONDS AS PURE MASS REACTANCE

BODY RESONANCES (Hz)	AXIS OF VIBRATION		
	X-X	Z-Z	Y-Y
WHOLE BODY	5-7	3-5	2-3
ABDOMEN-THORAX	(5-6)*	3-4 (60)*	?
HEAD			(3-6, 20-30)*
LOWER JAW	6-10, 14-16	6-10	6-10, 14-16
EYES	10-12, 14-16	5, 15, 30, 40-70	5-8
SHOULDER	?	(7-10)*	2-3
ARMS	?	30-40	?
PELVIS	6-8	10-12	?
SPINE	?	8	?

*BASED ON SITTING OR STANDING TEST DATA



DATA COMBINED FROM 12 SOURCES

FIGURE 1 - PERFORMANCE LIMITS - SINUSOIDAL VIBRATION SEMI-SUPINE

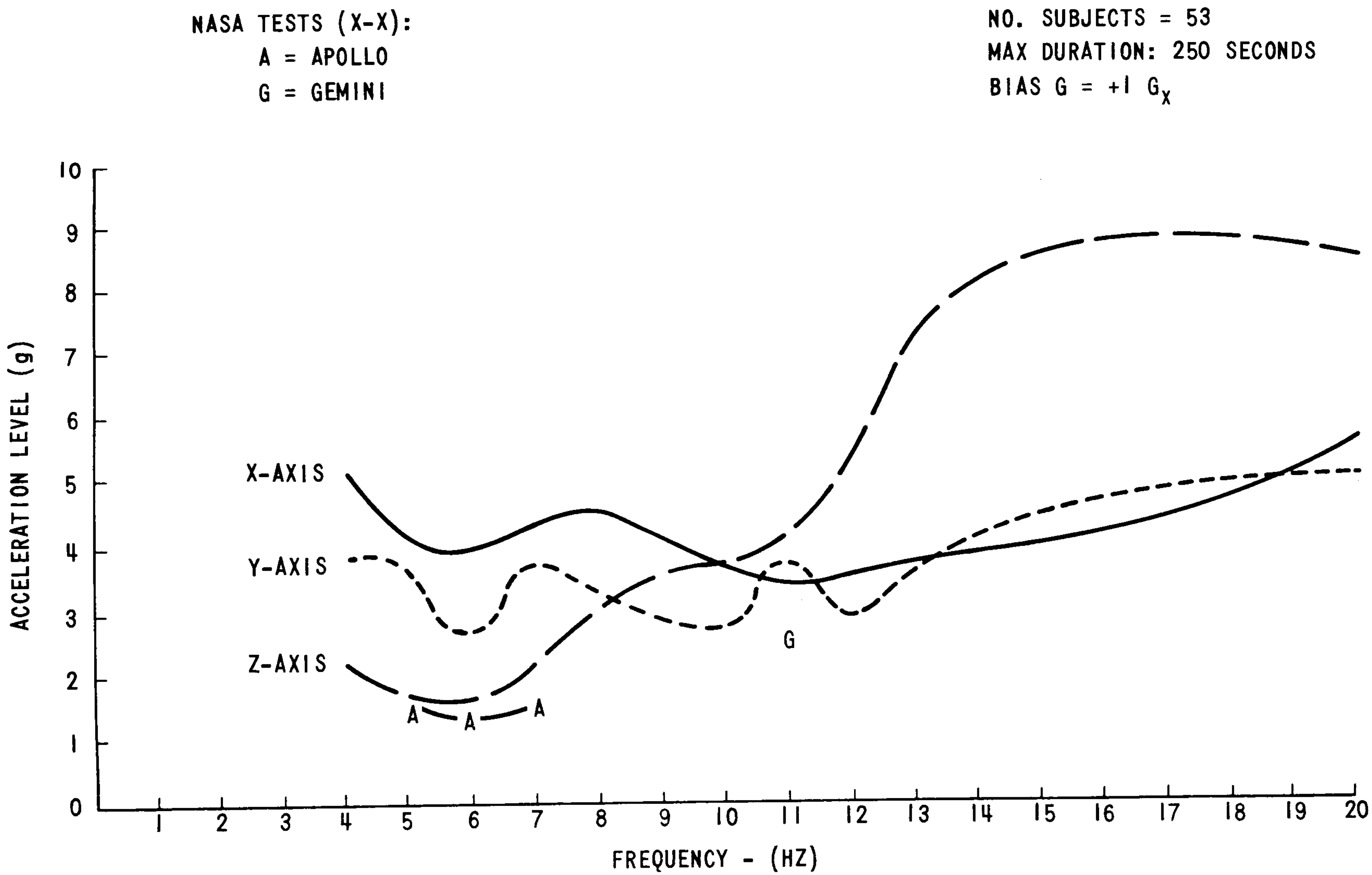


FIGURE 2 - TOLERANCE TO SINUSOIDAL VIBRATION SEMI-SUPINE ADJUSTABLE COUCH

MECHANICAL FORCES - IMPACT

STATEMENT OF THE PROBLEM

Avoidance of impact forces is necessary to the survival of most organisms, including man. Impacts are decelerative forces, analogous to a half-cycle vibration of large magnitude, but composed of a wide spectrum of frequencies because of their non-periodic nature. The effects of these forces are extremely complex, being influenced by such factors as the magnitude, direction and duration of the deceleration, and the type of protection used, body posture and state of relaxation.

Increases in the speed of most forms of transportation have brought increases in the injurious and lethal possibilities of impact beyond man's capabilities to survive unprotected. In space flight especially, significant impacts are a normal part of the landing procedure, since truly "soft" landing methods have not yet been developed. U. S. space flights have all used a water recovery procedure because acceptable light-weight systems for recovery on hard land are not yet available. Russian flights have used the land recovery method with reported success.

The capability to land safely on hard ground is under development. This will be useful for such contingencies as launch aborts or emergency reentry from orbit. In addition, the costly deployment of large naval forces necessary for recovery from a water landing may be significantly reduced after a satisfactory ground landing capability is available. Impact attenuation systems must provide crew protection under both nominal and contingency landings, and tolerance data must be available for their design.

PAST MEDICAL APPROACH

NASA's efforts on impact problems have had two major aspects: (1) investigations of the physiological and subjective effects of deceleration profiles along the major body axes, with supplementary accident data providing information on tolerance limits, injurious and lethal levels; and (2) development of impact attenuation criteria for space missions and the evaluation of restraints and impact protection systems. The major physiological effects of impact are summarized in Table 1.

The design of impact attenuation systems for the Mercury program used fragmentary human and animal impact tolerance data from Air Force studies. Impact severity was held within these tolerance limits by a form-fitting couch, a pneumatic bag, and by controlling the vertical sink speed. Emergency impact protection was provided by an aluminum honeycomb crushable support system for the couch. Volunteer human drop tests verified the acceptability of the recommended landing impact limits and the system proved effective in the actual missions.

In the Gemini program the Command Module was suspended under the parachute in a tipped position so that it entered the water somewhat edgewise, thus reducing the initial impact shock. An escape hatch, ejection seat and personal parachute for each crewmember served as an emergency escape system. The Gemini ejection seat design was based upon military ejection seat data and emergency ejection experience.

The tipped Command Module concept used for Gemini was used for the Apollo mission water landing. Instead of an ejection seat system, however, the couches were supported by impact attenuation struts and the lower edge of the Command Module was designed to be crushable and, therefore, provide additional impact attenuation.

PRESENT MEDICAL POSITION

Human experiments on the factors related to impact tolerance and injury levels are inherently dangerous. The available data is, therefore, largely based on volunteer human exposures and animal studies. Sufficient information now exists from such studies to establish normal mission impact limits. Continuing study in this field is being directed toward development of mathematical models for describing impact effects.

The envelope of the Apollo normal mission impact limits is presented in Figure 1. The forward and backward acting limits are a 20g resultant throughout the allowable range of lateral and longitudinal accelerations. The lateral limit is a 10g component throughout the allowable range of longitudinal and transverse accelerations. The trailward acting limit is a 15g resultant throughout the allowable range of longitudinal and lateral accelerations. The headward acting limit is a 15g component throughout the allowable range of longitudinal and lateral accelerations. The rate of onset of acceleration is limited to 10,000g per second for forward and backward acting forces, 1,000g per second for lateral forces, and 500g per second for headward and tailward acting forces. For intermediate directions (those directions that have approximately a 45° forward or backward acting component) the rate of onset is limited to 1,000g per second.

Emergency impact limits for Apollo are defined in MIL-Spec 9479 (USAF).

FUTURE EFFORTS

The ground landing concept proposed to supersede the water landing and recovery procedure is based upon steerable sailing parachutes and a final retro-rocket or flare-out procedure to decrease the vertical descent speed to acceptable values. Failure of the steering system or control of the final descent speed then will create an emergency. For this reason, emergency impact systems must be provided and studies made with the subjects loaded to the threshold of injury or with a small risk of reversible injury accepted.

Accordingly, NASA should subsidize or undertake the following programs:

a. For forward acting impact forces (eye-balls in) determine the most probable impact injuries and the relation between their incidence and the acceleration time history. This study should include velocity changes well beyond those expected in normal operations.

b. Repeat the above study for the vector combinations of headward, forward and lateral forces encompassed by the lower posterior quarter of a sphere encompassing the human body.

c. Evaluate the effects of a long (700 day) exposure to weightlessness on decrease of bone, ligament, and muscle tissue strength.

d. If weightlessness has a debilitating effect, develop remedial measures or determine the modifications that must be made to the limits previously discussed.

Human subjects cannot be used for studies of emergency impact limits, either morally or legally. Animal studies are of some limited value, but the correlations between animal and human tolerances are not known. Therefore, it is necessary to use animal surrogates and scaling approaches to study these survival and injury limits. Such scaling procedures must be developed so that the most nearly representative animals can be chosen and so that the correlation factor between these animals and man can be determined. These studies require several years of lead time and thus should be started in the very near future.

All of the above work can be done with ground based equipment that exists or is being developed. This fact is a distinct advantage if the lead time now available is utilized for productive work on these limits with candidate attenuation systems.

Full scale drop tests of prototype vehicles similar to those conducted in previous programs will be necessary to validate the effectiveness of the impact attenuation systems.

TABLE I

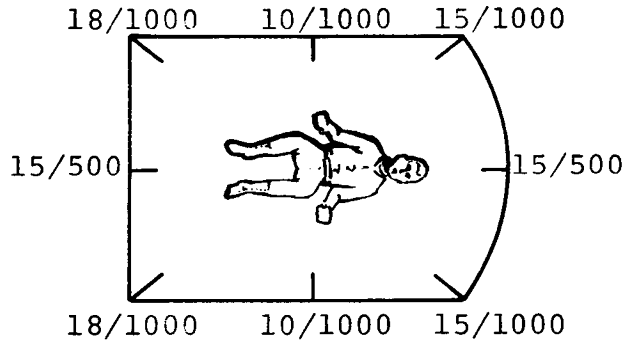
GENERAL BIOLOGICAL EFFECTS OF IMPACT

A REVIEW OF EXPERIMENTAL EXPERIENCES WITH IMPACTS PRODUCED BY SHORT TRACK DECELERATION DEVICES HAS SHOWN THAT THERE ARE NUMEROUS PHYSIOLOGICAL CHANGES FOLLOWING IMPACTS IN THE TRANSVERSE ($\pm G_x$) DIRECTION WHEN THE PEAK FORCES RANGE FROM 15 TO 25 G, AND ONSETS RANGE FROM 400 TO 1000 G/SEC. THESE ARE TRANSIENT CHANGES, AND OCCUR IN SUBJECTS WHO ARE ENTIRELY UNINJURED IN THE MECHANICAL SENSE OF BONE FRACTURE OR DETECTABLE TEARING OF TISSUES AND ORGANS. THE PHYSIOLOGICAL CHANGES ARE SUMMARIZED IN THE FOLLOWING TABLE.

EFFECT	NOTES
SHOCK	BLOOD PRESSURE 90/60 mm Hg ROUTINELY SEEN 15-30 SEC AFTER IMPACTS PRODUCING 15-20 $\pm G_x$ PEAKS, WHERE ONSET RATE WAS 500 G/SEC. LOWER PRESSURES OBSERVED AFTER GREATER IMPACTS.
BRADYCARDIA	SLIGHT SLOWING OF HEART RATE (BRADYCARDIA) FOLLOWING 15 G PEAK IMPACTS FACING FORWARD ($-G_x$), AND GREATER SLOWING IN BACKWARD FACING IMPACTS ($+G_x$). THE EFFECT WAS RELATED TO ACTIVITY OF THE VAGUS NERVE, SINCE ATROPINE BLOCKED THE BRADYCARDIA. AT GREATER PEAK ACCELERATIONS, GREATER SLOWING OCCURRED.
TRANSIENT NEUROLOGICAL CHANGES	SUBJECTS APPEARED TO BE STUNNED FOR 10-15 SECONDS AT 20 G PEAK ACCELERATIONS (ONSET AT 400 AND 800 G/SEC), AND ABNORMAL SLOW WAVE PATTERNS WERE SEEN ON THE ELECTRO-ENCEPHALOGRAM FOR SEVERAL MINUTES FOLLOWING PEAK IMPACTS AT 25 $+G_x$, 1000 G/SEC ONSET. OTHER CHANGES INCLUDED INCREASED MUSCLE TONE, EUPHORIA, LOQUACITY, HAND TREMOR, DECREASED COORDINATION, AND GROSS INVOLUNTARY MOVEMENTS IN HEAD, ARMS, AND TRUNK. INCREASED DEEP TENDON REFLEXES WERE COMMONLY PRESENT AFTER $\pm 15\ G_x$, AND AFTER A PEAK IMPACT OF 25 G REFLEXES WERE ABSENT FOR SEVERAL SECONDS, THEN HYPERACTIVE FOR ABOUT A MINUTE.
CHANGES IN BLOOD PLATELETS	ONE HOUR AFTER IMPACTS WITH $+20\ G_x$ PEAKS AND ONSETS OF 400 OR 800 G/SEC, BLOOD PLATELETS WERE FOUND TO BE REDUCED. A WEEK LATER THE PLATELET COUNT WAS HIGHER THAN THE CONTROL VALUE.
PSYCHOLOGICAL CHANGES	PSYCHOLOGICAL EVALUATION WITH THE KAHN SYMBOL ARRANGEMENT TEST SHOWED CHANGES WHICH INCREASED WITH $+G_x$ IMPACTS FROM 10 TO 25 G PEAK ACCELERATIONS.
GENERAL STRESS REACTIONS	CHANGES WERE SEEN IN THE INDICATORS OF ADRENAL GLAND ACTIVITY, AND VARIOUS CHANGES OCCURRED IN CHEMICAL CONSTITUENTS OF THE BLOOD.

APOLLO NORMAL MISSION IMPACT LIMITS

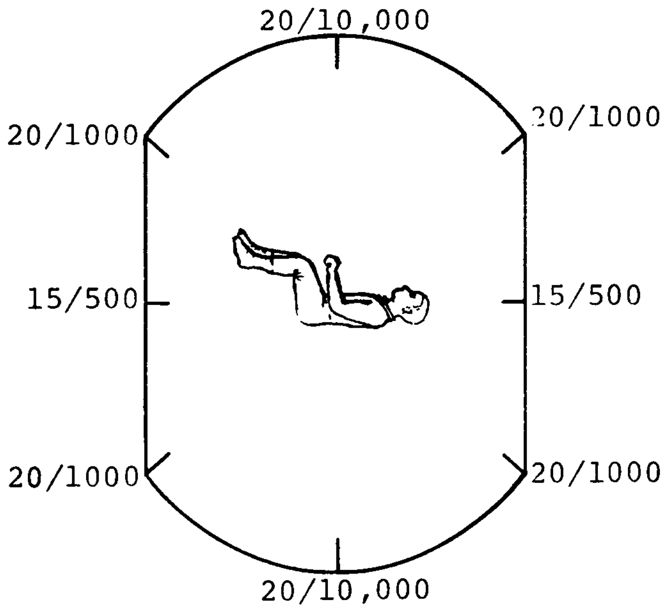
Coronal Plane Section



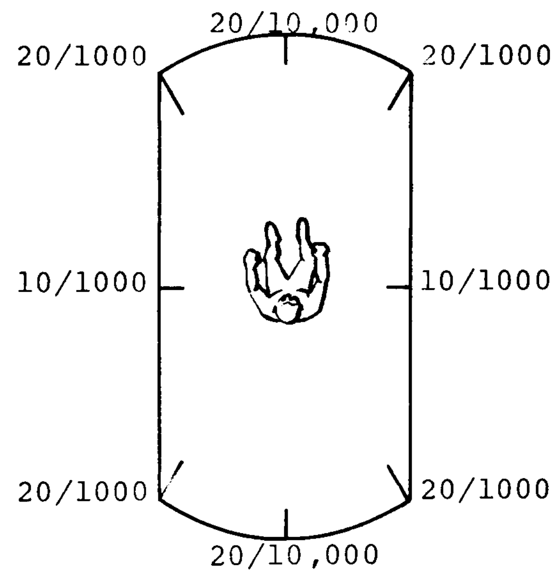
NOTE:

a. Restraint and support similar to Apollo configuration.

b. Arrows indicate direction, magnitude, and on-set rate of maximum acceptable applied acceleration force for normal mission limits.



Saggital Plane Section



Transverse Plane Section

FIGURE 1

MECHANICAL FORCES - NOISE AND BLAST

STATEMENT OF THE PROBLEM

Noise is distinguished from acceptable aspects of the auditory environment by its excessive intensities, and relative lack of informational content. Excessive noise levels have long been known as an industrial hazard which can interfere with effective communications, degrade general performance, induce nausea or disorientation and produce temporary or permanent deafness.

During launch, noise generated by the rocket engines in the immediate environment of the spacecraft far exceeds normal levels in industrial and jet aircraft operations. During acceleration through the lower levels of the atmosphere aerodynamic buffeting may also present a noise hazard. Experience to date, however, indicates that buffeting during re-entry does not represent a significant noise problem.

Efficient crew performance during prolonged missions may also be affected by the lower levels of continuous and intermittent noise produced by onboard equipment. Our experience to date indicates that there is no need in normal operations to provide minimum noise levels in order to prevent the undesirable psychophysiological effects of isolation. The sound stimulation available is adequate for these needs and each man's capabilities to generate sounds for such self-stimulation are much greater than his capabilities to attenuate excessive sound levels.

Blast, or sonic over-pressure, is also a potential hazard whenever hypergolics or readily ignited rocket fuels and oxidizing agents are near each other. Accidental explosions have occurred in unmanned flights and could occur in future manned missions. Acceptable limits for sudden over-pressure impulses have been established by the Atomic Energy Commission and the Department of Defense, and these are discussed in greater detail in the section on Meteoroids.

Low-frequency, high-energy noise hazards are still inadequately defined. The problem is aggravated by the shifting of the maximum energy transmission into the frequency range below 100 cps associated with larger boosters. In the low-frequency range, the information available for evaluating physiological effects and establishing long-duration performance and tolerance limits is incomplete.

PAST MEDICAL APPROACH

Previous approaches to noise problems have had two major aspects. These are: (1) investigation of the physiological and performance effects of short and long duration exposures to noise of known frequency-intensity distributions, and (2) development of protective means for controlling the intensities of noise reaching the ear, and of communications systems with response characteristics which optimize the intelligibility of speech to and from crewmen in noisy environments. These protective developments have combined engineering efforts at:

(a) reducing the intensity of the noise source,

(b) providing noise attenuation material in the work environment, and

(c) acoustically isolating the men by personal devices such as ear plugs or headphones.

For the Apollo program the USAF has studied the low-frequency range below 100 cps by placing subjects fitted with ear plugs at selected positions within the noise fields of powerful jet streams, such as those produced by jet airplanes and the exit nozzles of supersonic blow-down tunnels. MSC has conducted a low-frequency study in which the frequency of the pressure pulsations imposed on the subjects varied from one to 12 cycles per second. Accordingly, the range between 10 and 100 cycles per second should be restudied using subjects without ear protection so that all data are on a directly comparable basis.

PRESENT MEDICAL POSITION

In the audible frequency range above 100 cps, well documented intensity limits are available in the literature for both brief and continuous exposures. These values will apply for NASA's purposes of establishing tolerance and general performance limits, articulation and intelligibility criteria and evaluations of communication equipment. Table I indicates allowable acoustical noise levels established for military aircraft crews operating under various conditions.

Brief exposures to broad-band noise levels up to 120 db are physiologically tolerable, but are not compatible with tasks involving communication. Pain and discomfort are produced when overall sound pressure levels exceed 135 db even briefly, and 150 db levels are associated with such non-auditory effects as disorientation, nausea and vomiting. The audible range below 100 cps, extending into the infra-sonic vibratory area, is still in need of further study.

FUTURE EFFORTS

The following research or study programs should be conducted in preparation for extended space missions. These programs, as with other programs in this general area, should consist of two general phases; a phase to provide the performance and tolerance limits, and an engineering measurements phase to evaluate whether the spacecraft design satisfies the human criteria.

The performance and tolerance phase should include the following programs:

a. Determine the interference levels of noise over the range from 1 to 100 cps, on the crew's capabilities to understand auditory signals and speech, produce intelligible speech, and perform psychomotor tasks.

b. Determine the tolerance limits for the frequency range between 10 and 100 cycles without ear plugs.

Special communication equipment must be used if ear plugs are required and this information must be available to system designers.

The engineering phase should include the following parts:

a. Determine the types of spacecraft structure and noise attenuation material which are needed to reduce the transmission of 1 to 100 cps noise.

b. Determine the noise transmitted to the astronauts' ears with a candidate spacecraft design, communications equipment, and prototype suit in a sound chamber. Sound pressure levels, speech intelligibility and speech interference levels should be measured using human subjects. The incident noise should simulate closely the expected noise spectrum.

c. Measure the noise transmitted through the spacecraft structure into the cabin to the locations of the crewmens' heads during an unmanned test flight.

d. Measure the noise attenuation, and speech transmission and hearing capabilities of the suit and helmet when exposed to the frequency spectrum and levels obtained during the unmanned flight test.

Comparison of the measured noise levels with the performance and tolerance data will determine whether the spacecraft satisfies the design specifications.

TABLE I

ALLOWABLE ACOUSTICAL NOISE LEVELS IN MILITARY AIRCRAFT AND HELMETS
(AFTER MIL-A-8806A)

FREQUENCY BANDS (Hz)	MAXIMUM ACCEPTABLE NOISE LEVELS (dB)		
	a) AT MAXIMUM CONTINUOUS POWER	b) UNDER SHORT DURATION CONDITIONS	c) WITH PROTECTIVE HELMETS OR DEVICES
37.5 - 75	111	118	111
75 - 150	111	118	111
150 - 300	111	118	111
300 - 600	105	112	109
600 - 1200	99	106	106
1200 - 2400	93	100	100
2400 - 4800	87	94	94
4800 - 9600	87	94	94
OVERALL	113	120	113

MICROBIOLOGY

STATEMENT OF THE PROBLEM

Within the space vehicle, man exists in a dynamic relationship with his microflora, those of the other crew-members, and those that may be free living within the space-craft. In this situation the man-microbe ecological patterns will tend to reach new equilibria that are the complex resultant of the combined physical and biological factors that prevail. To insure that this new equilibrium is compatible with man's health and survival is the basic goal of the microbiology program.

Analysis of the generic problem of infectious disease control in manned space flight operations can be considered in several frames of reference:

a. Time (relative to flight).

b. Resistance to infection (inflight and postflight).

c. Spacecraft ecology.

d. Therapeutic strategies.

Figure 1 summarizes potential infectious disease problem areas along a time axis. It can be seen that catagorically different disease potential exists at the several epochal periods extending from prelaunch to postflight periods. The significance of the preflight period has been documented in Project Gemini (29).

The inflight potential has been postulated from microfloral shifts observed in animal and with less confidence, in man. The postflight potential results from altered host exposure during long-term flights that could result in decreased resistance after long-term missions. This has been discussed in detail in the review paper by Luckey (16).

Regarding the program from a host resistance point of view involves consideration of indigenous biochemical responses, as well as anatomic defenses, and the possible alteration of exogenous antigen that could accompany altered spacecraft microflora.

Approaching the program as a study in ecology results in a schema such as presented in Figure 2. This reflects the complex nature of the research effort required to predict what the final steady-state equilibrium will be during long-term missions. It is clear that the research strategies cannot be limited to either man, or systems, or environment, but must take all significant factors into account.

Lastly, the problem includes consideration of methods from chemoprophylaxis and therapy of infectious disease states occurring during long-duration space missions.

PAST MEDICAL APPROACH

The state-of-the-art of the microgiological aspects of manned space flight is characterized by an alarming paucity of data relating to the effects of space system environments on man and his microbiota. However, certain postulates on the microbial hazards of extended space flight may be advanced based upon the available data and problems encountered during exposure of experimental animals and man to variously modified environments wherein a "locked flora" was either created or maintained. In animals, as well as man, isolation in a modified "sterile" environment produces a decrease in the number of species of microorganisms residing in the nose, throat, mouth, gastrointestinal tract, and on the skin of the host (1-10). The information gained from these studies indicates that more often than not, imbalance of the "normal" microbial ecology places the host in a precarious position. It is well known that a balanced microbiota exerts a suppressing effect against an overgrowth by one or more species. Specific examples of the effects of imbalance are the numerous cases of rampant invasions by normally "harmless" microorganisms following drug therapy (11-14); the lethal effect of "nonpathogenic" E. coli seen when the organisms (S. faecalis or Lactobacilli) forming part of the biological system of checks and balances are removed from the host (15) and the heart lesions produced by "friendly" organisms (S. faecalis or B. subtilis) in monoflora hosts(16).

It is only recently that some of the effects of space cabin environments on susceptibility to infection have been defined in experimental animals. Exposure to these environments has produced for the most part lowered resistance to generalized bacterial infection (17-19); increased susceptibility and lower recuperative powers of the integument to infection with S. aureau (2); marked inhibition of interferon production (21); "bacterial flooding" (1) or evidenced by the appearance of E. coli in the oral cavity of test animals (22,23); and, increased susceptibility to pneumonia (18,24).

As in the studies with experimental animals, the limited amount of microbiological data available from manned chamber studies and space flights in the United States and Russia indicate that there are areas of potential serious concern for the health of astronauts. In three of five chamber tests, there was evidence of transfer of microorganisms between subjects (20) with the replacement in one subject of the normal flora of the nose with a pure culture of S. aureus (8). Other chamber studies indicate that the resultant isolation from the "normal" environment produces a change in both the number and types of skin and intestinal flora (25-27). Tests from Gemini flights have revealed microbiological phenomena representing potential ecological imbalance as evidenced by a simplification of species accompanied by an increase in total numbers (28).

The extended duration of future space missions and the possible provision of sterile air and water will provide the equivalent of a classic "locked flora system" The available data indicate that the chance of microbial insult occurring in such a system is one of high probability. The level of confidence in this already high probability figure increases in proportion to the length of the mission, the degree of isolation, and the reduction of exogenous microflora input.

The balance reached between a host animal and its microbiota is a precarious one in spacecraft ecologic systems, and even minor changes in diet or physiologic state may affect a new balance of the microflora in which the dominant species may or may not be compatible with the well-being of the host.

PRESENT MEDICAL POSITION

A. Current Acceptable Limits

The following list reflects the most imperative first-order decisions for insuring crew health and safety.

1. Health status preflight - To the extent possible, the crew must be quarantined for a sufficient period of time (two weeks) to insure that infections in the incubation phase can be recognized and treated.
2. Inflight microbial load limits
    a. Man - none specified
    b. Aerosol - the aerosol load limit should be reduced by proper air filtration devices to less than 100 particles/cubic meter.
    c. Surfaces - build up of microbial contamination on spacecraft surfaces shall be minimized by eliminating potential nutrient sources.

d. Food system - microbial decomposition of food remnants must be eliminated.

e. Water system - water quality criteria for the potable water system is given in the section on water management. No build-up of microbial populations in the wash water or humidity condensate systems can be allowed.

f. Waste management system - surfaces coming in contact with or contaminated by biological waste material must be cleansed and disinfected to prevent microbial growth. Microbial decomposition of waste materials must be eliminated.

3. Inflight therapy and/or prophylaxis - See the section on Clinical Medical Care.

4. Immune status preflight and inflight - Acceptable limits not specified.

B. Current Program

The microbiology protocols for Apollo missions have been greatly enlarged over those employed during the Gemini program. Extensive microbiological analyses, employing specimens of blood, urine, feces, throat washings, skin swabs, and samples from the spacecraft are performed to define the preflight and postflight microflora burden and immunologic status of crewmembers and determine the microbial load of the spacecraft interior. Information derived from data analyses will be used to:

1. improve the probability of mission success and utilization of the prime crew by permitting the early recognition and treatment of infectious disease conditions during the preflight period,
2. determine the affects of space systems environmental parameters on the microbiota of each crewmember as shown by significant changes between preflight and postflight flora and to determine variations in microbial balance which may be harmful,
3. ensure a minimum crew quarantine period by defining illness events, which may occur either during or after the flight, in terms of specific etiologies,
4. provide data for missions of extended duration regarding possible alterations in microbial ecology and immunity and specific recommendations for control.

FUTURE EFFORTS

A. General Objectives

1. Ground-Based Studies

Extensive ground-based studies must be accomplished to insure the health and well-being of the crew for long-term flight. These studies should develop an understanding of the complex relationship that exist between man and his total microbial environment within a closed system. Provisions for controls and preventive measures can then be made.

2. Preflight

Prior to long-term flight, the capability must be obtained to provide an acceptable microflora for the crew, spacecraft and environmental control system. An acceptable microflora would be one that does not produce problems in the host and one that remains compatible with the microflora of other crewmembers. Pathogens must be eliminated and preventive measures must be taken to control opportunist organisms capable of causing illness.

It is well known that many "nonpathogens" are capable of producing problems to the host when they are subjected to adverse conditions. Potential microbial hazards will likely exist as long as microorganisms are present in the enclosed environment of the spacecraft.

To counteract this possibility, methods for maintaining a balanced ecological state must be studied. Implantation of "normal" microorganisms continues to be an excellent possibility. Protective immunity must be given to the crew prior to the flight, to provide for possible microbial unbalance during the flight. This requires that an acceptable immune status be defined for the crew, in conjunction with the defined microflora.

3. Inflight

Ground-based studies for inflight microbial problems must develop an understanding of the effect of the spacecraft environmental factors on man, on the microflora and on the man-microflora relationship. Once these interrelationships are understood, methods can be developed for control or elimination of factors that lead to an unbalanced system and possible infection.

Each factor, until shown otherwise, must be considered as a possible agent for altering man, microorganism or the man-microorganism relationship in some manner. In fact, several factors together may induce an effect on the balance between man and microflora. Once an undesirable change occurs, in the form of illness, attempts to correct the unbalanced condition with chemicals or antibiotics, may compound the problem.

4. Postflight

Crewmembers returning from long-term missions are expected to be carrying a simplified microflora, as indicated by the present data. During the period of flight in the enclosed system, the normal state of immunity will have decreased, or may be nonexistent. This loss in resistance, due to lack of contact, will be not only to pathogenic organisms but to those normally considered nonpathogenic. Ground-based studies must be initiated to define the problems of readjusting the crew to a "contaminated" environment, and to determine methods for accomplishing this.

B. Specific Research and Development Areas

The development of space vehicles is, unfortunately, far more advanced than our present knowledge or ability to provide man with a habitable environment. The main objective of the microbiological research program is to reduce this knowledge gap by pursuing a coordinated course of action and study leading to the qualification of man for extended duration missions in space. A program of requirements in three phases is presented below. The required studies are delineated by the task objectives with logical progression from Phase A to Phases B and C.

Phase A - Determine nature and extent of problems

Task: Formulation and testing of hypotheses

1. Appropriate experimental animal-environmental models and descriptive laboratory-epidemiologic techniques will be used to establish principles and define biological trends with statistical precision.
2. Analytic laboratory-epidemiologic techniques will be applied to specific events as related to the health of man.

Required Studies: Microbial diseases in animals and man in spacecraft environments

1. Development of space environment test facilities for comparative medical studies,

2. microbial dynamics in spacecraft ecologies,
3. microbial imbalance and endogenous disease states,
4. effects of spacecraft environments on susceptibility to infection,
5. damage to specific host systems and lowered resistance,
6. effects of spacecraft environments on cellular and humoral immune mechanisms,
7. effects of spacecraft environments on microflora as related to increased virulence,
8. activation of latent or inapparent infection; conversion of dormant infection into overt disease,
9. development of improved methods for growth and identification of the "normal" microflora and understanding the biological characteristics and role *in vivo* of such organisms,
10. development of methodology and hardware for inflight storage of specimen material to enable retrospective etiologic diagnosis of illness events occurring during the inflight mission phase, and
11. effects of space flight diets on the microflora of the gastrointestinal tract and effects of change on man.

End Products: Definition of determinants of disease

1. Accumulation of knowledge that is relevant to the response the host makes to exposure to spacecraft environmental parameters over defined time intervals,

2. conceptual separation of determinants of disease from determinants of infection,
3. nature of causal associations -- direct, indirect, primary, secondary, specific etiologies, and
4. problem definition and concurrent extension into Phase B and Phase C.

Phase B - Derivation of methods of prevention and control

Task: Control of problems peculiar to the spacecraft environment.

1. Ensure that spacecraft-adjusted microbial ecologies and interrelationships within the host-microbe com-complex are compatible with man's health and survival,
2. tailor preventive medical procedures and therapeutic regimens to meet the problems peculiar to the spacecraft ecological situation, and
3. investigate all man-machine interfaces to ensure rational hardware design.

Required Studies: Control of microbial diseases in spacecraft environments

1. Support research and development of methods and techniques for detecting "pre-clinical" disease states,
2. develop rationale for providing crewmembers with an "acceptable" microflora and immune status during the preflight period,

3. devise methodology (such as implantation of food with a defined microflora) for maintaining a microbial balance which is compatible with crew health,
4. provide rationale for efficacious therapeutic regimens which will not compound problems arising from microbial imbalance,
5. develop meaningful criteria of design for spacecraft which will ensure a habitable environment, and
6. devise methods for control of microbial environmental contamination.

End Products: Definition of control measures

1. Accumulation of knowledge that is relevant to the "qualification" of man for extended duration missions in space,
2. development of new techniques for early detection of physiological and pathological alterations having microbial etiologies,
3. development of concepts and techniques for controlling, within desirable limits, the quantity and quality of man's microfloral burden, and
4. assurance of mission success by ensuring that the spacecraft environment is compatible with man's health and survival.

Phase C - Microbiological, ecological monitoring

Task: Microbiological monitoring of crewmembers, spacecraft and life support system

1. Real-time monitoring of crewmembers for evidence of potentially harmful microbial shifts and/or etiologic diagnosis of illness events occurring inflight,
2. real-time monitoring of spacecraft, including environmental control systems, and water reclamation and waste management systems for evidence of microbial contamination and systems failure, and
3. inflight collection and storage of specimen materials coupled with postflight microbiological analyses.

Required Studies: Development of techniques and flight qualified hardware

1. Support research on techniques of preserving viability of microorganisms during long-term storage of specimen materials,
2. provide crewmembers and the aero-medical flight controller with information required for objective decision making in go-no-go situations,
3. provide the laboratory data which is basic to the problem of defining changes which occur as "normal" ecologies revert to "spacecraft-adjusted" ecosystems, and
4. provide the information required for recommendation of therapeutic regimens and determining efficacy of preventive medical practices proposed for ensuring crew health and safety during prolonged space missions.

C. Engineering Implications

Throughout the microbiology program, imperative engineering interfaces are present. These include:

a. Devices for inflight microbial assessment.

b. Environmental control system design.

c. Waste management system design.

d. Waste management systems and water reclamation systems.

e. Personal hygiene devices, e.g., hand washing, oral hygiene, whole body bathing devices.

f. Spacecraft design as it concerns:

  (1) Spacecraft construction materials which function as nutrients for microflora.

  (2) Wall temperatures.

  (3) Radiation shielding.

  (4) Leakage rates.

  (5) Purge procedures.

Close surveillance of the above programs is imperative to an understanding of the microbial ecology within the spacecraft. More importantly, it is primarily through these systems that the microflora can be regulated. Thus, meaningful design criteria must be evolved to provide guidance to the engineering groups which will be designing the advanced systems for long-term flight.

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FIGURE 1

TIME-FRAME ANALYSIS - PROBLEM AREAS

PRELAUNCH	LAUNCH + 14 DAYS	INFLIGHT	POSTFLIGHT
INFECTIOUS DISEASE STATUS. FOOD STRESS QUARANTINE.	INFECTIOUS DISEASE STATES ACQUIRED PREFLIGHT WITH INCUBATION PERIODS SUCH THAT CLINICAL ILLNESS IS REVEALED POSTLAUNCH.	1. SECONDARY DISEASE STATUS RESULTING IN A PREDOMINANCE OF ANOTHER AGENT WHICH IS PATHOGENIC UNDER THIS CONDITION. 2. SECONDARY DISEASE STATUS RESULTING IN A REDUCED HOST RESISTANCE TO INFECTION.	DISEASE STATE DUE TO ALTERED HOST RESISTANCE ACQUIRED DURING FLIGHT

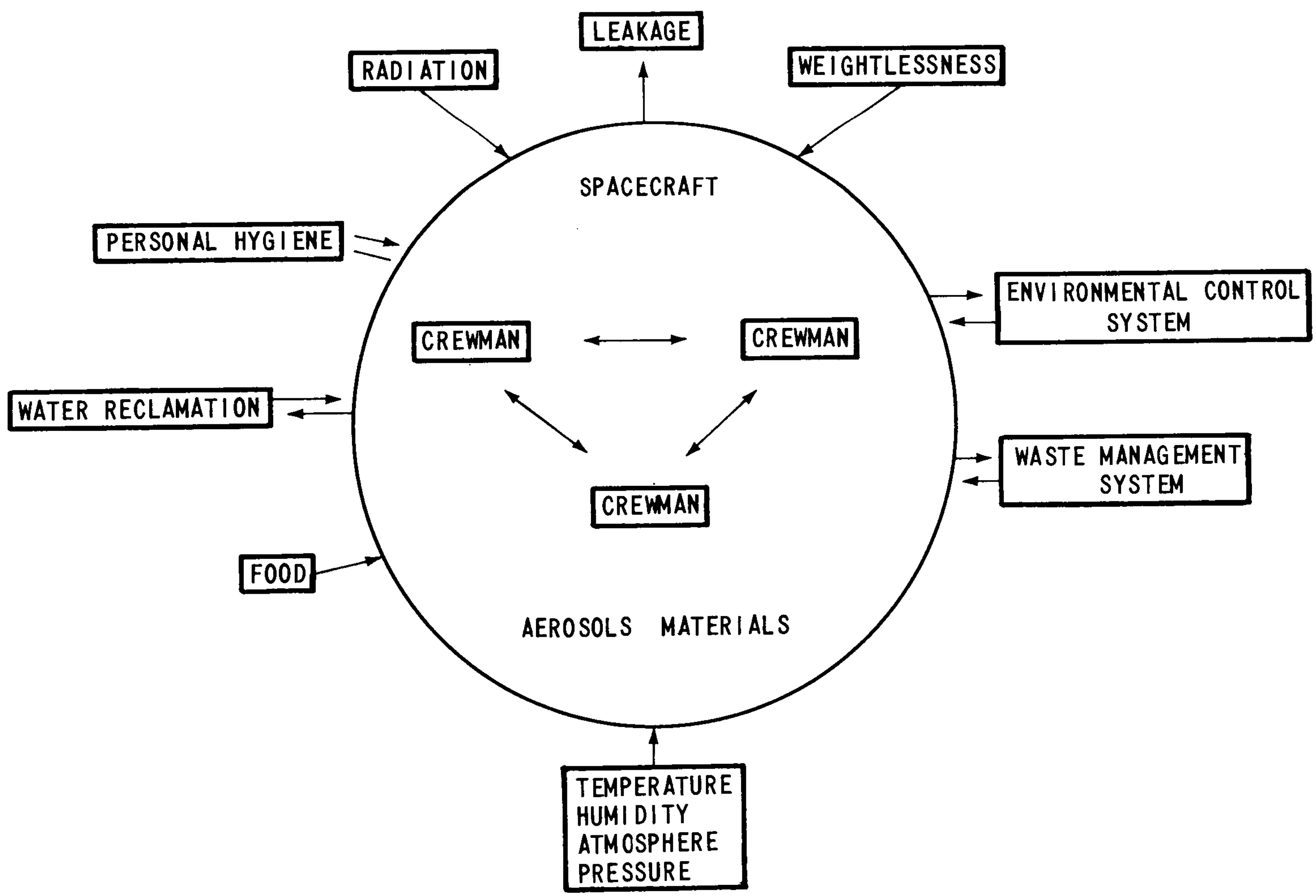

FIGURE 2 - SPACECRAFT ECOLOGY SCHEMA

TOXICOLOGY

STATEMENT OF THE PROBLEM

The problem of removal of contaminants, limiting contaminants, and establishing acceptable levels of contaminants presents a number of engineering and medical problems. In the future, outboard spacecraft leaks will be greatly reduced, if not eliminated, resulting in an increased accumulation of contaminants. Human contribution to the atmospheric contaminantion will assume increased significance, while low rates of outgassing and deterioration will produce long-term contaminant buildup. Carbon dioxide levels and the nature of the atmosphere may have significant effects on the toxicological responses; however, the removal of toxic contaminants by absorptive techniques using a replacement approach such as activated charcoal would impose too great a weight penalty to be useful for long-term missions.

There is a paucity of data describing the response of man and lower animals to continuous, uninterrupted exposures to trace contaminants. Industrial exposure limits are based upon 8-hour-per-day exposures for 5 days per week on the premise that no permanent, irreversible damage shall occur. Emergency limits for exposures resulting from spills or repairs are currently those established by the National Research Coucil Committee on Toxicology for submarine use and are likewise based upon the reversibility of damage produced by a single massive short-term exposure.

Consideration has been given to establishing a long-term threshold limit value for all potential contaminants at a fixed fraction of each one's 8-hour threshold limit value. This approach is not adequate even for design purposes, since it ignores cumulative effects of specific compounds, irreversibility, synergism between compounds, and differences in mode of action and target organs.

Sources of contaminants and responses to these contaminants must be evaluated. During continuous, uninterrupted exposure, either adaptation to the intoxicant or cumulative responses may occur. Predictive models must be developed based upon a knowledge of human and animal metabolism of, and responses to specific toxic agents.

Two criteria must be considered in establishing the limits of change. The first is the reversibility of the change; thus, irreversible and cumulative toxic manifestations as are observed in the effects of halogenated hydrocarbons on the liver would be considered completely unacceptable. Changes resulting from adaptation through the formation of adaptive and detoxifying enzymes must be considered in terms of the rate of adaptation and the ease and rate of reversal of the adaptive phenomenon after the stressor has been removed.

The second factor to be considered is the potential for decrement in performance, resulting in an inability to complete the mission objectives. For this purpose, mission objectives must be categorized into primary, secondary, and lower levels, in order to determine the extent of performance decrement which would be considered acceptable.

In consideration of the limits of acceptable physiological responses, thought must be given to the limitations of the amounts of contaminants originating from the multiple sources within the spacecraft. Control of the contaminants by contaminant removal systems, specially designed if necessary, will provide an additional margin of safety. Prophylactic measures may be introduced in the event that interactions occur between weightlessness and toxic stressors. Such prophylactic measures may run the gamut from the institution of an artificial gravity force to drugs or dietary supplements affecting the detoxication of the contaminant.

Establishment of the critical responses will require knowledge of the contaminants anticipated in the spacecraft, which result from the humans occupying it and the equipment supporting them. Toxicological studies on lower animals and subhuman primates, and comparison with human exposure experience, will establish the criteria for extrapolation of animal to human exposures.

PAST MEDICAL APPROACH

Control of atmospheric contaminants has been largely based upon generalized methodologies (charcoal absorption) with little regard to the identification of the contaminants to be removed, their biological implications, or their sources. Limits have been set for total hydrocarbon outgassing of materials selected for spacecraft use and upon the amount of specific toxic agents which a given material may emit under specific conditions. This general approach, which involves charcoal absorbers and chemical carbon dioxide scrubbers has been adequate for relatively short-term missions where charcoal and lithium hydroxide scrubbers can be replaced before depletion, and where low rates of outgassing and nonregenerative systems have been acceptable. This general approach cannot be used in long-term missions.

The reduction in contaminant levels by means of the relatively high spacecraft atmospheric leak rate has been assumed adequate for those components not removed by the scrubbers, and catalytic burners have not been incorporated in the environmental control system. With the continuing reduction in leakage rates, build-up of contaminant concentrations to unacceptable levels may occur. The major offenders are methane, hydrogen and carbon monoxide, a metabolic by-product whose interference with human performance has been demonstrated at very low levels.

PRESENT MEDICAL POSITION

The current standards for atmospheric contamination levels are those recommended in "Atmospheric Contaminants in Spacecraft", National Academy of Sciences, October 1968. For Chemical contaminants not contained in the above report, a hundredth of the Industrial Threshold Limiting Value shall be used. Since the presently employed activated charcoal absorbents do not remove the hydrogen, methane and carbon monozide, a catalytic burner should be used on all extended missions. For the relatively short-term space flights, contaminant removal using replaceable absorption canisters, coupled with strict limits on the amount and kind of outgassing products coming from the nonmetallic components placed in the spacecraft crew quarters, is assumed to insure an acceptable, non-toxic atmosphere. This is verified by outgassing analysis of test and flight vehicles. The major concern in the current programs is the presence of vapors and aerosols resulting from fluid leaks and the pyrolysis products which result if over-heating of nonmetallic material occurs. The present approach to these problem areas is directed towards eliminating those materials which pose potential hazards. Detection of trouble inflight depends primarily upon the crew.

FUTURE EFFORTS

General Contaminants

To achieve the objectives of flight safety and mission completion the following research and development programs are required:

1. A determination of the contribution of humans to the gaseous, particulate, and aerosol contamination of the atmosphere. This determination should be performed upon a sufficiently large population to determine the significance of human contribution. Human production of carbon monoxide should be evaluated to determine its importance relative to the offgassing of carbon monoxide by spacecraft components. Weber (1963) calculated that over 400 contaminants would

be put into the spacecraft atmosphere by human occupants. These contaminants would be in the form of gases, particulates, and aerosols. Conkle (1966, 1967) reported finding 21 gaseous contaminants produced by human occupants of a closed environmental simulator. The quantitation and significance of these results should be determined and verified.

2. Define the contaminants contributed by the spacecraft components and introduced by supplies. The contaminants result from the offgassing and aging of nonmetallic materials, accelerated aging and thermal degradation resulting from heating, contaminants contained in the makeup gases of the environment, gases produced by the regenerative systems, and those contaminants introduced into the atmosphere as a result of routine and emergency repairs and maintenance.

3. As part of the overall contaminant evaluation, the contribution of microbial and fungal action on excreta, metabolites, and spacecraft components should be determined.

4. It will be necessary to determine the effects of prolonged, continuous exposure on the threshold levels for various atmospheric contaminants. Criteria for establishing these threshold levels must be based upon

behavioral, physiological, and biochemical criteria. These studies should include evaluations of the interactions between physiological responses resulting from space flight and responses to toxic components in the atmosphere.

5. Since the capability for decompressing and "revitalization" of the atmosphere will be extremely limited in a long-term mission, emergency exposure limits must be established for contaminants introduced during routine and emergency maintenance and repair.
6. Inflight monitoring equipment for gases, aerosols and particulates must be developed to provide a means for evaluating the atmospheric status.
7. Human and animal exposures to specific contaminants and combinations of contaminants must be able to evaluate potentially dangerous situations. In connection with this, physiological and biochemical models should be developed for relating animal and human toxicological data to produce more reliable extrapolation from animals to humans. The information so obtained should be utilized in the development of prophylactic measures against accidental or intentional overexposures.

ENRICHED OXYGEN ATMOSPHERE - RED CELL MASS LOSS

STATEMENT OF THE PROBLEM

In the Gemini IV, V and VII, flights hemolysis of the red blood cells was observed in five of six crewmembers exposed to the flight environment for intervals of 4, 8 and 14 days.* This hemolytic process reduces the ability of the blood to transport oxygen to the tissues and during demanding physical tasks reduces the work capacity of the astronauts.

Because of the paucity of the available data, little reliable information is on hand with which to predict the time course, extent, or consequence of this hemolytic process. Space flight factors which are believed to cause loss of red cell mass include:

1. Abnormally high pure oxygen atmosphere which facilitates deleterious chemical reactions at the surface of the red cell and interferes with red cell metabolism; and
2. Relative crew inactivity combined with weightlessness which reduce the oxygen exchange and blood flow requirements in the tissues.

In addition:

1. Chronically enriched oxygen atmospheres may suppress the production rate of red cells;

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*"Pre-Gemini Medical Predictions Versus Gemini Flight Results" C. A. Berry, p. 197-218 in "Gemini Summary Conference" NASA SP-138(1967)

2. Dietary insufficiency of vitamin E (α-tocopherol) may reduce the resistance of the red cell membrane to oxidation; and
3. Weightlessness may have a direct effect on the production or destruction rates of red cells via some currently obscure process.

Presently the available data is insufficient to permit speculation as to whether the observed decrement in red cell mass is of an adaptive or deleterious nature.

PAST MEDICAL APPROACH

Minimal information is presently available relative to the effects of weightlessness on the red blood cells and precursors in the bone marrow. Null-gravity simulations, such as bed rest and water immersion have been extensively studied but primarily with regard to cardiovascular deconditioning and bone demineralization. Little information has been published about the effects of these weightlessness analogs on the interaction between bone marrow, circulating red blood cells and the reticuloendothelial system. Past experience is particularly sparse with regard to combined stresses such as weightlessness, diet and hyperoxia. Hyperoxia per se has been studied in many ways by many invesitgators, but animals have been the primary test subject for these investigations. This animal oriented approach has ignored diet as an important factor affecting red cell membrane composition and, therefore, overlooked a significant variable. The relative few human hyperoxia exposures were primarily aimed towards operationally validating the currently accepted space cabin atmosphere rather than examine any invoked affects on the blood system.

Pre- and post-flight testing has been utilized to directly observe the effects of weightlessness and other combined space flight stressors. This program has included a comprehensive study of red cell structure and physiology. The salient facts collected thus far include:

a. A reduction in red cell mass during flight intervals, associated with a shortened $^{51}Cr\ T\frac{1}{2}$ and postflight reticulocytosis.

b. A reduction in plasma tocopherol levels in the six crewmembers studied for this variable.

c. Quantitative and qualitative alterations of the plasma membrane lipids and fatty acid pattern of each lipid. Specifically, these changes include reduction of total membrane lipid and loss of long chain unsaturated fatty acids from each constituent lipid.

d. Increased intraerythrocytic sodium.

e. An increased mean corpuscular volume, decreased mean corpuscular hemoglobin concentration and osmotic fragility shift.

f. A significant acanthocytosis, spherocytosis, and microspherocytosis after 14 days of space flight.

No in-flight countermeasures against red cell hemolysis have been attempted in Mercury or Gemini or are any planned for Apollo.

PRESENT MEDICAL POSITION

1. Weightlessness is an acceptable variable relative to the hematological system for human exposures lasting up to 30 days.

2. For exposures over 30 days, additive and/or synergistic conditions, such as hyperoxia, relative inactivity and diet, must be re-evaluated. It is not presently possible to predict the hematological reactions to flight durations of more than about 30 days.

3. If it is found that the red cell loss is progressive, ameliorative measures must be taken. In descending order of desirability, the following corrective measures can be applied:

a. Specific therapy based on the revealed etiology of the red cell loss.

b. Regular exercise.

c. Periodic inhalation of low pO_2.

d. Oral medication for general erythropoietic stimulation, such as cobolt.

e. Parenteral medication for general erythropoietic stimulation, such as androgens.

However, only after more is known about the time course and extent of the space flight related hemolysis can implementation of any of the above remedial measures be recommended.

4. Adequate red blood cell mass for comfort in the basal state under normal air pressure and composition can be quite different from that required for heavy work, such as EVA, under

hyperoxic or hypoxic conditions. The hemoglobin levels and the expected symptomatology for a two-gas atmosphere with alveolar pO_2 approaching 104 mm Hg (normal level) are as follows:

a. 8.0 g percent - tachycardia

b. 7.5 g percent - dyspnea on exertion

c. 6.0 g percent - headache and vertigo

d. 5.0 g percent - marked weakness

e. 3.0 g percent - dyspnea at rest

f. 2.0 g percent - coma

Based on these values, 8.5 g percent of hemoglobin is the lower limit for unrestricted crew safety and mission success.

5. The astronaut diet should not be deficient in vitamin E (α - tocopherol). This condition is easily met.

FUTURE EFFORTS

Ground based R and D

Areas of investigation include:

1. Effects of weightlessness analogs on red cell membranes, metabolism and enumerative characteristics.
2. Effects of combined stressors such as weightlessness analogs, hyperoxia, diet and relative inactivity on the red blood cell and their precursors in the bone marrow.
3. The role of "inert" diluent gases on red cell physiology.

Inflight Measurements and Procedures

To better establish the true time course of any flight related loss in red blood cell mass, a multitude of inflight tests should be employed. Tests selected for in-flight application must be chosen with the following criteria in mind: (a) safety, (b) accuracy and reproducibility, and (c) operational simplicity. The use of techniques such as impedance counting, specific tone electrodes assay, ultramicrospectrophotometry and electron probe analysis are but a few of the analytical modes to be employed.

Animal studies could also be used to look at specific mechanisms as suggested by the human work. It is imperative, however, to utilize animals which are quite comparable to man in the parameters of interest.

ENERGY METABOLISM

STATEMENT OF THE PROBLEM

Physiological Considerations

The most basic process of living systems is production of energy by metabolism. The energy derived from these processes is used for physiological and biochemical functions, permitting the organism to perform work.

There are two basic reasons why energy metabolism should be a consideration for the qualification of man for long duration missions. First, in the planning of logistics and life support systems it is necessary to have a reliable estimate of food and oxygen requirements, as well as expected thermal loads during various phases of a mission, i.e., during rest, exercise, and required activities (particularly those in a pressurized suit). Although the extrapolation of ground-based data is sufficient for estimating short term requirements, missions of a year or longer require that more accurate energy metabolism data be collected in-flight.

The second consideration is the physiological consequence of the combined environmental factors of space flight on man's efficiency and ability to do work. Weightlessness, atmospheric composition, and confinement are the most unique properties of the space flight environment. The biological systems where one might first expect to observe any effects of these factors are the cardiovascular, pulmonary, and muscular systems. The integrity of these systems is a definite limiting factor to energy metabolism and performance, and therefore, man's ability to function in the space environment.

Technical Considerations

When an individual is not moving or working and has not recently eaten, all of the energy appears as heat. During this condition, energy production can be directly measured by direct calorimetry. However, this covers only a small portion of the time when total energy measurements are required.

Energy production can also be calculated using indirect calorimetry which measures the O_2 consumed. Since oxygen is not stored (except for about 1 liter as oxyhemoglobin and myoglobin in the blood and tissues), its consumption keeps pace with immediate needs and is proportionate to the total energy produced. One problem with using only O_2 consumption as a measure of energy production is the fact that the energy released per mol of O_2 is dependent upon the food being oxidized. Although an estimate of 4.82 k cal/mol O_2 is accurate enough for most purposes, the actual values can be determined from an analysis of the respiratory quotient (RQ), which requires that CO_2 production (during steady state conditions) be measured simultaneously with O_2 consumption.

For space flight applications the measurement of 0_2 consumption and CO_2 production will be necessary in a pressure environment of 3.5 - 8.7 psi having a considerably higher oxygen percentage than under terrestrial conditions. Since measurements are planned both for steady and non-steady state physiological conditions, it is desirable to have continuous measurement of these variables. An additional restriction imposed upon equipment and procedures is limited weight and volume, ease of operation, and handling of data.

The measurement of energy production through the use of indirect calorimetry has been accomplished clinically and in the laboratory using two general methods, the closed circuit and the open circuit. Excellent discussions of these two types of measurement can be found (Consolazio, et. al., 1963; Best and Taylor, 1961; Bard, 1961; Bartels, 1963.) In the closed system the subject rebreathes from a container which contains 100% oxygen and a carbon dioxide absorber. The 0_2 consumption is then determined by the decrease in volume of the system or by the amount of 0_2 added to keep the volume constant. If carbon dioxide production is desired, the CO_2 absorber must be weighed or analyzed, or be assessed by a system that determines volumes before and after CO_2 absorption. Luft (1958) has reviewed spirometric methods which have been used for closed circuit indirect calorimetry.

The standard open circuit method of determining metabolic rate is based on minute volumes and gas concentrations. Usually only expired volume (collected in a spirometer-Tissot Method, in a bag-Douglas Method, or measured with a dry gas meter with a portion of gas being saved for analysis-Kofranyi-Michaelis respirometer) is measured, as well as its O_2, CO_2, and N_2 content. From these values it is possible to calculate inspired volume and therefore V_{O_2}, V_{CO_2}, and RQ. Because of the inflight restrictions already mentioned, it is not possible to use any of these standard laboratory techniques in their present form.

The advantages and disadvantages of a closed system are summarized in Table 1. Although it may be possible to overcome some of the engineering and technical problems associated with a closed circuit device, there is another aspect to be considered. The ultimate aim of metabolic measurements during space flight will be to accomplish them during EVA and while working on the surface of the moon. Since the necessary size of a closed system device makes it impractical in these applications, the development of such a system should be viewed an interim measure, at best.

The standard open circuit method does not have many of the limitations imposed by closed circuit methods, but it does have a basic limitation for space applications. When breathing 100% O_2 (necessary for EVA operations), it is not possible to calculate inspired volumes on the basis of expired nitrogen concentrations. When the RQ is not 1.0, the calculated oxygen consumption is in error due to inspired-expired volume differences. A summary of the advantages and disadvantages for the standard open circuit is found in Table 2.

There are other open systems which should be mentioned because of their possible application to space flight measurements. With the advent of an accurate oxygen analyzer, a system for measuring metabolic rate was developed in which an excess air flow directed past the organism is analyzed for the percent decrease in O_2 content. A general description of this technique and corrections for RQ have been published (Depocas and Hart, 1957; Margaria, et. al., 1954).

Kissen and McGuire (1967) have developed an oxygen consumption computer based on the measurement of expired volume using a mass flow meter and oxygen concentration using a polorographic sensor. This device is produced commercially and is presently being evaluated.

Another open system oxygen consumption device is used in which a variable speed fan in a feedback loop is used to keep the partial pressure of O_2 at a set level. The voltage required to drive the fan is proportional to oxygen consumption.

Although it would be possible to construct a separate metabolic system that would function best in each of the planned applications (and environments), the success of this program depends upon comparative measurements made under conditions in which the principal investigator is not always conducting the experiment. In addition, the high cost of space flight hardware, as well as weight and volume limitations, require that a single system be developed.

Summarizing the requirements for a metabolic analyzer:

(1) Small weight and volume.

(2) Operation must be simple and of no hinderance to the astronaut.

(3) Must function across a wide range of atmospheric composition and pressure variations with little change in accuracy (including pressure suit operation).

(4) Results must be comparable to standard laboratory techniques.

(5) Response of system should follow non-steady state physiological conditions during space flight operations.

(6) Data reduction should be an integral part of system.

In view of these factors, it is felt that at the present time there is no developed system which meets these requirements.

PAST MEDICAL APPROACH

Inflight

Metabolic rate measurements during the Mercury and Gemini programs have been limited to the chemical analysis of the LiOH cannisters following space flight. This method, at best, gave only an indication of the average energy expenditure for the entire crew over the duration of the mission. Figure 1 is a summary chart of these average energy expenditures. Because these have been short flights with relative inactivity, these results are of limited value in predicting man's energy requirements for long duration missions.

Although it is too early to estimate the energy requirements of EVA, a review of the five Gemini EVA's revealed that severe stress was imposed upon the respiratory system in two of the excursions. Information from the flights and from ground-based tests indicates that a heavy workload would not in itself cause the observed dyspnea but that it could be reproduced by an interaction of physical and biomedical factors, namely thermal stress, increased levels of pCO_2, and emotional imponderables.

Pre-Postflight

In addition to inflight measurements, preflight and postflight exercise capacity tests were conducted on six of the Gemini astronauts. When looking at mean values, maximum oxygen consumption decreased 7%, metabolic rate decreased 9%, systolic blood pressure increased 5%, diastolic blood pressure increased 10%, and time on the bicycle ergometer to a heart rate of 180 decreased 14%. The significance of these indicators of decreased work performance cannot be determined until more data is collected and analyzed.

PRESENT MEDICAL POSITION

If man is to be qualified for long duration missions, it is imperative that energy metabolism data be collected inflight. This is required because of logistics and life support requirements, as well as the possible physiological degradation of work performance.

Until inflight data can be collected, it is also required that energy metabolism and work performance, as well as pulmonary function, be evaluated pre- and postflight. Should a physiological degradation of ability to do work be evident, an acceptable limit of this degradation will have to be established. These limits will be determined by required activities for the successful completion of a mission, considerations relating to the mechanism behind the degradation, and whether countermeasures are possible.

The life support systems both in the spacecraft and the suits for EVA and lunar surface operations must be adequate to accomodate the functional work capacity (both sustained and transient thermal loads) of the typical astronaut. While the work capacity in the spacecraft is not likely to exceed that of aircraft pilot in the geogravitational environment, this cannot be said of EVA or lunar operations, where an emergency may raise the metabolic level to that experienced during heavy exertion on earth. Fletcher (1964) has compiled data from several sources (Figure 2), to show metabolic curves for "first class athletes" and "healthy men" engaged in exerting activities (running, rowing, cycling, etc.) under normal atmospheric conditions. The design criteria for the life support systems for EVA and lunar operations should be such as to permit the levels of activity shown by Fletcher, thus providing for those emergencies in which these higher metabolic levels are called for.

FUTURE EFFORTS

At the present time it is planned to elucidate the problems of energy metabolism by pursuing the following inflight experimental plan: M171 - Metabolic Costs of In-flight Tasks. Metabolic rate (oxygen consumption, carbon dioxide production, and respiratory quotient) is to be measured during rest, calibrated exercise (bicycle ergometer), and operational type tasks. The resting metabolic rate and the metabolic rate during calibrated exercise are to be measured in an unsuited mode, while the operational type tasks are to be done both in suited and pressure suit (3.7 psi above the 5 psi workshop environment). In addition, this entire set of measurements is to be repeated throughout the mission to determine the effect of mission duration.

In order to evaluate results obtained inflight, ground-based data is to be obtained on each crewmember during all of the experimental configurations. Additional ground-based data is to be obtained in separate simulation studies.

As has already been stated, there are many technical problems associated with making metabolic measurements under space flight conditions. Therefore, considerable effort will have to be expended to develop the necessary hardware and procedures before successful inflight measurements can be realized. Many components will be required to be state-of-the-art. After integration into a suitable system, extensive physiological testing will be needed to verify the design and procedures.

With these factors in mind, it is our recommendation that the design of a metabolic analyzer be pursued with the following priorities:

General Components

1. A highly accurate, wide dynamic range, compact flowmeter with necessary corrections for STPD in any habitable environment.
2. An accurate, compact gas sensor which simultaneously measures oxygen, carbon dioxide, nitrogen, and water.
3. A compact data handling system.

Specific Systems or Techniques

1. An open system which measures all inspired and expired parameters over incremental periods of time.
2. An open system which measures all inspired and expired parameters on a breath-by-breath basis.
3. An open system using excess gas flow.
4. A closed system of compact design.

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TABLE I

CLOSED SYSTEM

ADVANTAGES	DISADVANTAGES	UNKNOWNS	DEVELOPMENT STATUS
1. O_2 CONSUMPTION ONLY MAKEUP GAS REQUIRED	1. VOLUME	1. HANDLING H_2O VAPOR AT REDUCED PRESSURES	1. READILY AVAILABLE AS LABORATORY OR CLINICAL TECHNIQUE FROM COMMERCIAL SOURCES
2. RESPIRATORY GAS CAN BE KEPT SEPARATE FROM AMBIENT	2. REQUIRES COMPACT AND EFFICIENT CO_2 ABSORBERS FOR HIGH WORK RATES	2. CLEANING	2. IN-HOUSE PROTOTYPE CONSTRUCTED USING WATERLESS SPIROMETERS
3. ACCURACY	3. DIFFICULTY IN OBTAINING RESPIRATORY VOLUMES	3. EFFECT OF SUIT PRESSURE FLUCTU-ATIONS ON REFER-ENCE SIDE OF CLOSED LOOP	3. INDUSTRY RFP PROPOSALS
	4. CHANGES IN FRC RE-GISTERED AS CHANGE IN O_2 CONSUMPTION		
	5. CO_2 PRODUCTION MUST BE MEASURED SEPARATELY		
	6. MAINTAINING THERMAL EQUILIBRIUM FROM HEAT PRODUCED BY CO_2 ABSORPTION		
	7. CLOSED VOLUME MUST BE REF-ERENCED TO SUIT PRESSURE WHEN USED IN PRESSURIZED SUIT		
	8. SUBJECT-SYSTEM INTERFACE MUST BE LEAK-PROOF		
	9. REQUIRES N_2 WASHOUT TIME WHEN USED IN MIXED GAS ATMOSPHERE		

TABLE 2

STANDARD OPEN CIRCUIT

ADVANTAGES	DISADVANTAGES	UNKNOWN	DEVELOPMENT STATUS
1. DO NOT NEED SEPARATE AIR SUPPLY	1. UNABLE TO CALCULATE INSPIRED VOLUME FROM EXPIRED N_2 WHEN IN 100% O_2 ENVIRONMENT	1. EFFECT OF CHANGES IN INSPIRED O_2 OR CO_2	1. READILY AVAILABLE AS LABORATORY TOOL
2. VOLUME	2. REQUIRES HIGH ACCURACY FOR VOLUME AND PARTIAL PRESSURE MEASUREMENTS WHEN MEASURING NET VOLUMES OF INSPIRED AND EXPIRED GASES		2. ATTEMPTS BY NORTH AMERICAN AVIATION TO BUILD SYSTEM USING COMMERCIALLY AVAILABLE MASS FLOW METERS AND GAS SENSORS
			3. EVALUATION OF PERKIN-ELMER AEROSPACE MAGNETIC SECTOR MASS SPECTROMETER FOR GAS ANALYSIS

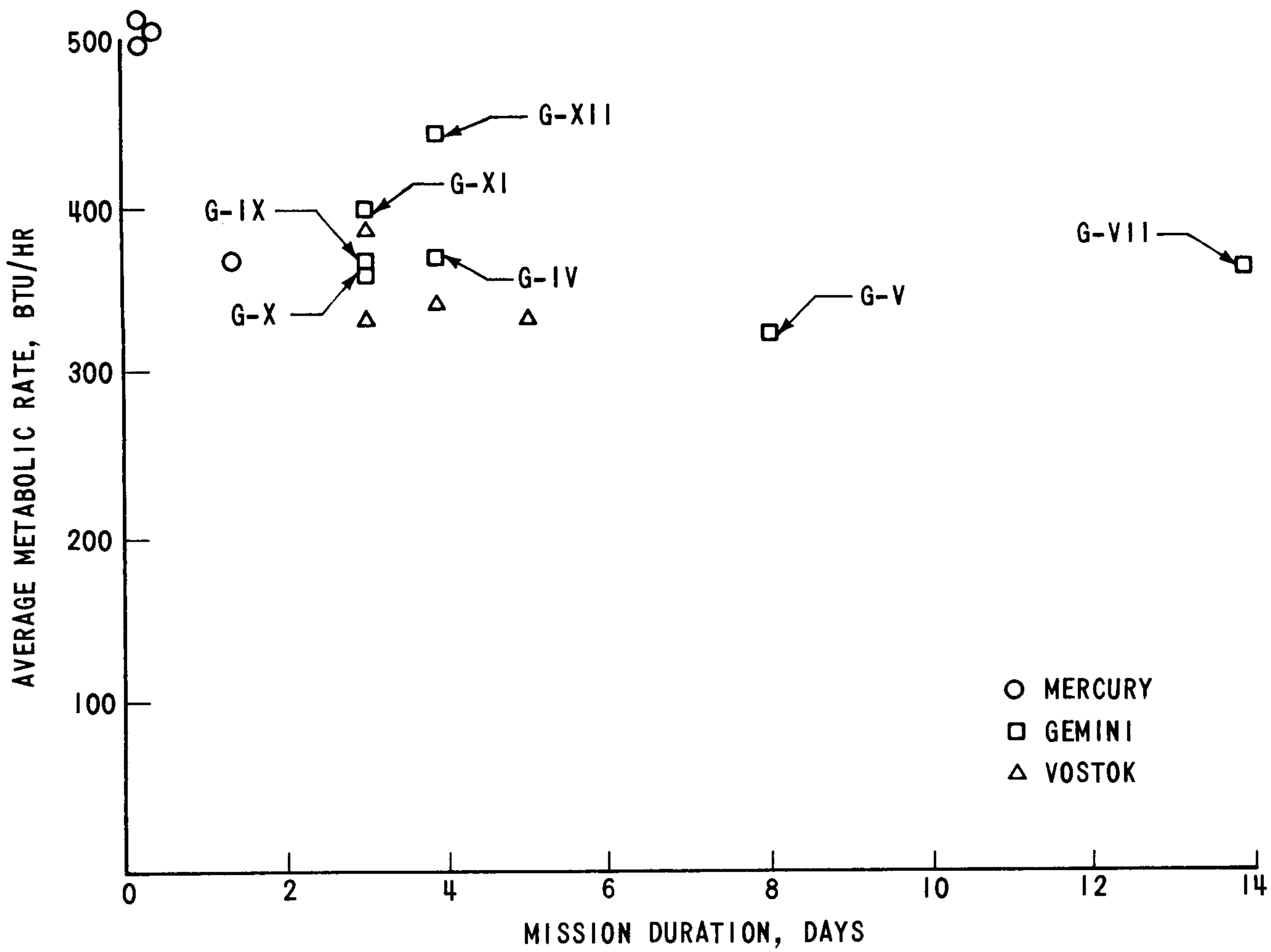

FIGURE 1 - AVERAGE METABOLIC RATES DURING ACTUAL SPACEFLIGHT

MAXIMAL WORK

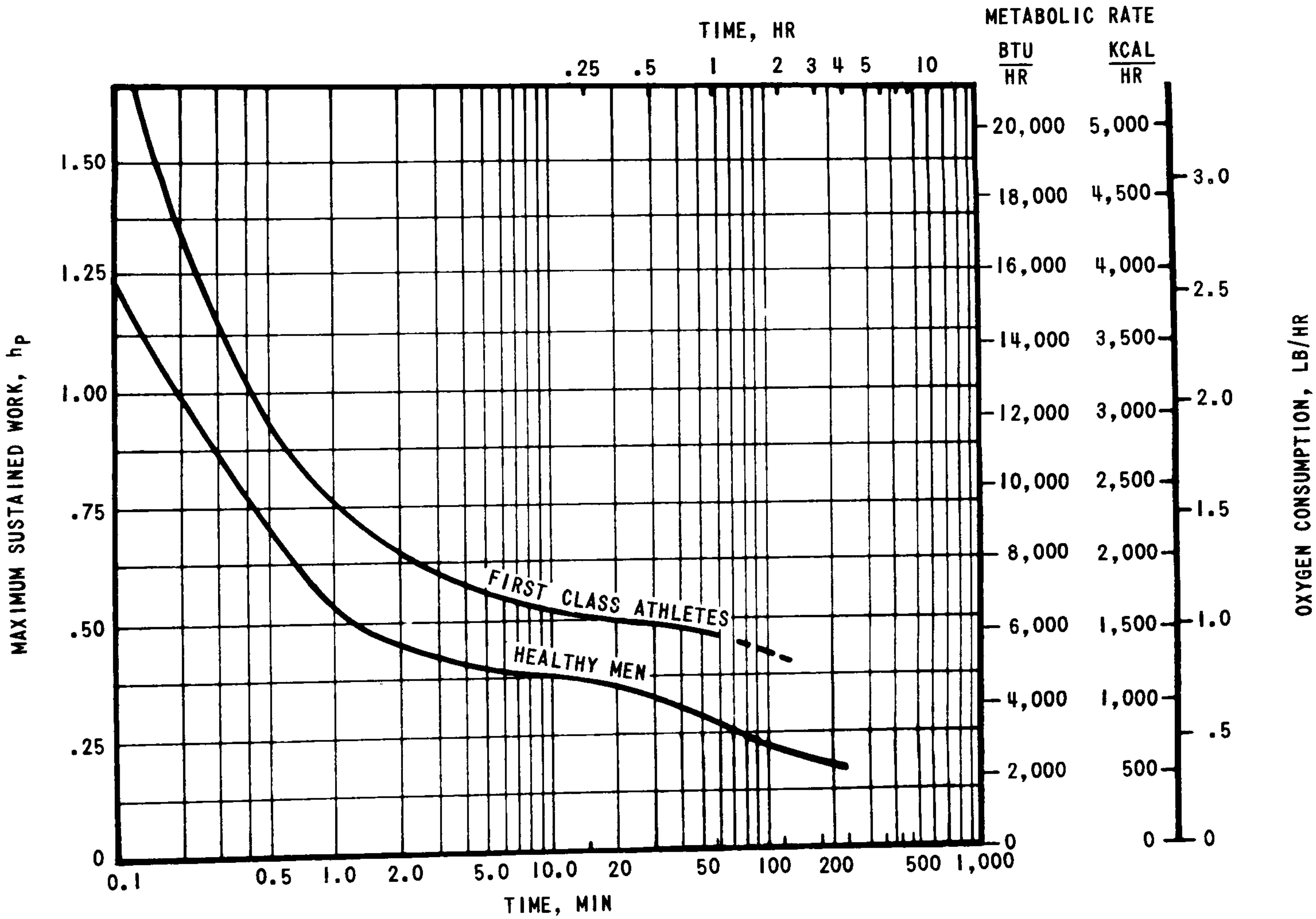

FIGURE 2 - MAXIMUM SUSTAINED WORK CAPACITY

CABIN ATMOSPHERE

STATEMENT OF THE PROBLEM

Obviously, the best atmosphere to support life processes is one identical in pressure and composition with that on Earth. In practice, however, space cabin atmospheres should be optimized from the standpoint of physiological functioning, systems reliability, ease of entering and leaving the intravehicular environment for extravehicular tasks, and reduced combustion propagation characteristics. Factors affecting the selection of space cabin atmospheres are considered below.

Oxygen Starvation

The most important consideration in the selection of space cabin atmospheres is the requirement to maintain the alveolar partial pressure of oxygen at no less than approximately 104 mm Hg (2 psia). Any reduction below this limit may compromise astronaut performance. For pure oxygen atmospheres the minimum ambient pressure necessary to provide this environment to the alveoli is approximately 187 mm Hg (3.5 psia). Oxygen starvation (hypoxia) may ensue if subnominal conditions develop as a result of ECS malfunctioning, excessive cabin leakage, or build-up of gaseous contaminants which replace molecular oxygen at constant total pressure. Ambient oxygen pressures higher than 187 mm Hg (3.5 psia) are, therefore, required to provide an adequate margin of safety.

Oxygen Toxicity

A alveolar partial pressure of oxygen above 104 mm Hg (2 psia) may cause the appearance of toxic signs and symptoms. The nature and severity of these symptoms depends on both the oxygen pressure and the duration of exposure to this pressure. Long term exposure to an alveolar partial pressure of oxygen around 258 mm Hg (5 psia) may cause respiratory, hematological and renal symptoms.

Carbon Dioxide Toxicity

Carbon dioxide has a powerful stimulatory effect on respiration as well as marked influences upon acid-base balance. Hence, the problem of carbon dioxide removal and the ability of man to perform adequately under conditions of various levels of carbon dioxide have become important. Carbon dioxide buildup may have contributed to the marked dyspnea reported in some of the Gemini EVA.

Atelectasis

Oxygen is absorbed readily from temporarily obstructed spaces in the body such as the air sacs (alveoli) of the lungs, the middle ear and the sinuses. In the absence of a mechanical support provided by a diluent gas, a significant pressure differential can develop between the outside and the inside of these spaces when obstructed. This situation results in ear (aural atelectasis) and sinuses pain and collapse of the air sacs of the lungs (pulmonary atelectasis). The latter is manifested by reduction in vital capacity and is aggravated by breath-holding and g-loads. In general, the lower the ambient pressure, the higher becomes the probability of atelectasis.

Dysbarism

The use of a diluent gas in space cabin atmospheres introduces the hazard of dysbarism. During a rapid transition from a higher to a lower ambient pressure environment, the diluent gas normally carried in solution in to the bloodstream is released through the formation of gas bubbles. The presence of bubbles in the cirulatory system can cause severe joint pains (called dysbarism or the bends) and could lead to cardiovascular or even nervous-system collapse. The rate of bubble information depends on both the nature of the diluent gas and the pressure reduction ratio. Dysbarism is a potential hazard following operational decompressions from the intravehicular to the spacesuit environment or following loss of the pressure integrity of the space cabin.

Performance Under Suited Conditions

The pressurized suit mode increases the metabolic expenditure required for the performance of normal tasks. This is caused primarily by the suit resistance to flexure which is directly proportional to the differential pressure between the inside and the outside of the spacesuit. Consequently, optimization of performance efficiency requires that the pressure of the spacesuit be as close to the physiologically acceptable lower limit as possible. This consideration affects in turn the intravehicular pressure environment in view of the dysbarism hazard during operational decompressions.

Fire Hazard

Oxygen in the pressure range required to support life presents a potential fire hazard. Tests confirm that the ignition temperature decreases and the rate of combustion increases with increasing oxygen partial pressure or decreasing diluent gas partial pressure. At fixed ratio mixtures of oxygen to diluent gas, flammability increases with increasing total pressure. A significant experimental result is that a pure oxygen atmosphere in the range 3.5 psia to 5.0 psia will not reduce the fire hazard to controllable limits. The increase of combustion rate from a sea level equivalent atmosphere to a 5.0 psia pure oxygen atmosphere is about a factor 4. Conversely, the decrease of combustion rate from 5 to 3.5 psia of oxygen is at the most about a factor of 1.2.

Engineering Considerations

The total pressure and composition of space cabin atmospheres is also influenced by two engineering requirements: minimum weight and maximum reliability.

The structural weight required to assure cabin integrity increases with increasing differential pressure across the hull of the space vehicle. More weight is also required for the application of a two- instead of a single-gas system. Furthermore, the complexity required for the monitoring and regulation of a two-gas environmental control system makes this an inherently less reliable system than its single-gas counterpart.

PAST MEDICAL APPROACH

In the early stages of the manned space flight program, technological constraints such as payload boost capability, systems simplicity and systems reliability demanded that a single gas atmosphere be used. Pure oxygen at a 5 psia total pressure was selected for both Project Mercury and Gemini.

Physiological research on space cabin atmospheres encompasses both pure oxygen and mixed gas environments. Uncertainties existed regarding oxygen toxicity at 5 psia (258 mm Hg) at reduced atmospheric pressure as well as the necessity for an inert gas in an artificial atmosphere. Accordingly, a comprehensive atmosphere validation program was instituted by NASA in cooperation with the National Academy of Science Working Group on Gaseous Environments. Both industrial and Department of Defense laboratories were utilized in the program. Data obtained from these continuing studies indicated that exposure of man for 14 days to a 100% 0_2, 5 psia atmosphere imposed no physiological limitations. As a result of those findings, the Apollo Program Office elected to utilize this atmosphere in their program.

Subsequent atmosphere validation tests of durations as long as 30 days indicated that the 100% 0_2 5 psia atmosphere was physiologically adequate. These as well as earlier studies clearly indicated, however, the association of this atmosphere with undesirable effects such as aural atelectasis, eye irritation, and nasal congestion.

Studies on the physiologic effects of mixed gas atmospheres other than air are few in number and controversial in nature. Existing evidence indicate that nitrogen is the optimum choice as a second atmospheric constituent from an overall medical standpoint. In addition, it could be that nitrogen is physiologically active in support of normal respiration, rather than the inert constitutent of air as current textbooks hypothesize. On the other hand, the disadvantages of nitrogen (e.g., dysbarism) at a total pressure of one atmosphere or less, are no worse than those of other candidate oxygen diluent gases. Research involving mixed gas atmospheres was, and is, mainly directed towards assessing the potential dysbarism hazard following decompressiong, and identifying procedures necessary to reduce the risk.

Medical investigations conducted in Gemini flights confirmed the occurrence of eye irritation and nasal congestion and provided suggestive but not conclusive evidence of hematologic changes related to the single gas atmosphere. The latter consists of a consistent time-related decrease in red cell mass. The causes and implications of this decrease in red cell mass are not completely understood.

As a result of these experiences, the use of a single gas atmosphere for long duration flight is highly controversial-- so much so that the scientific community is unwilling to extrapolate from the successful 30-day validation programs to longer duration missions without actual day-for-day validation.

PRESENT MEDICAL POSITION

1. A 5 psia pure oxygen atmosphere is acceptable for human exposures lasting up to 30 days.
2. For human exposures lasting longer than 30 days, a mixed two-gas atmosphere composed of oxygen and

nitrogen is recommended. Furthermore, this atmosphere must be designed to provide an oxygen partial pressure of 2 psia (or 104 mm Hg) in the lungs.

3. A space cabin atmosphere consisting of 70% O_2 and 30% N_2 at total pressure of 5 psia (180 mm Hg O_2 and 78 mm Hg N_2) is medically acceptable. From a physiological standpoint alone, however, a higher total atmospheric pressure is desirable.

4. Future generation spacecraft should have an environmental control system designed to provide an optimum mixed gas atmosphere from the standpoint of physiologic, safety engineering and operational considerations. Operational experience with a 5 psia oxygen-nitrogen atmosphere should be of material assistance in designing optimum spacecraft atmosphere criteria for very long duration flight.

5. The primary gaseous metabolic end product is carbon dioxide which is continuously removed by chemical reaction with replaceable lithium hydroxide canisters. The nominal carbon dioxide partial pressure is 3.8 mm Hg with a maximum of 7.6 mm Hg for continuous exposure. In emergency situations, a maximum of 15 mm Hg for no more than 30 minutes can be tolerated.

FUTURE EFFORTS

Ground Based R&D

Areas of investigation include:

1. Establishment of preoxygenation times required to protect against decompression.

2. Dysbarism hazards with a 50% O_2 - 50% N_2, 7 psia atmosphere.

3. Dysbarism hazards with a 50% O_2 - 50% He, 7 psia atmosphere.

4. Dysbarism hazards with a 70% O_2 - 30% N_2, 5 psia atmosphere.

5. Physiological effects arising from repeated decompressions.

6. Development of decompression tables for the safe ascent to altitude.

Results of recent investigations indicate that environmental carbon dioxide levels usually considered indifferent at rest may become critical in physical stress. Human studies must be continued to explore the physiologic mechanisms involved with the significant reduction of aerobic capacity demonstrated during exercise breathing inspired pCO_2 at predetermined levels.

Investigation of the potential hazard of respiratory infection is presently under way and will be continued. Preliminary results indicate a relative mean decrease in residual capacity of subjects with an upper respiratory infection (URI) when exposed to 100% O_2, 5 psia test conditions. One test subject also developed very rapidly marked evidence of pummonary telectasis. After completion of this pure oxygen series of tests the study will be extended to determine the most promising mixed gas atmosphere on subjects with URI and examine its physiological implications.

Although the 100% oxygen, 5 psia atmosphere is not a candidate on any space mission exceeding 30 days, the hematologic changes evidenced from pre- and post-flight data will remain under investigation.

Inflight Measurements and Procedures

In order to determine the effect of the spacecraft atmosphere on pulmonary physiology, it is necessary to assess the respiratory system in terms of function. Although there are many tests of pulmonary function which could be employed, those recommended for inflight use have been selected using the following criteria: (1) safety, (2) simplicity, (3) subject acceptance, (4) accuracy, and (5) repeatability. In general the function tests selected for inflight experimentation represent indices which can be considered separately or combined to give a comprehensive description of the overall performance of the pulmonary system.

In addition to repeating the tests planned for inflight, pre- and post-flight measurements include procedures which are not easily adaptable to inflight use but which evaluate additional important respiratory functions. A third level of sophistication will be pursued should the pre, post, or inflight measurements indicate impaired pulmonary function requiring an elucidation of specific mechanisms. These latter measurements would undoubtedly have to be done in laboratories with a well-established background in the specific test required.

Table 1 summarizes the pulmonary function tests at each of the three levels described above. They are listed according to the specific function they are measuring.

TABLE I

ASSESSMENT OF THE PULMONARY RESPONSE TO SPACE FLIGHT

NOTE: UNDERLINED INFLIGHT MEASUREMENTS REPRESENT THOSE WHICH DEPEND ON SUCCESSFUL EQUIPMENT DEVELOPMENT.

FUNCTION	METHOD	INFLIGHT	PRE-, POST-	ELUCIDATION OF IMPAIRED FUNCTION
VENTILATION	TIMED VITAL CAPACITY	X	X	X
	MAXIMUM FLOW	X	X	X
	MAXIMUM BREATHING CAPACITY			X
	GAS EXCHANGE	$\underline{X}$	X	X
TOTAL LUNG CAPACITY AND SUBDIVISIONS	SPIROMETRY	X	X	X
	NITROGEN CLEARANCE	$\underline{X}$	X	X
	HELIUM EQUILIBRIUM			X
	BODY PLETHYSMOGRAPHY			X
INERT GAS DISTRIBUTION	SINGLE BREATH NIGROGEN	$\underline{X}$	X	X
	OPEN CIRCUIT NITROGEN	$\underline{X}$	X	X
	ISOTOPE TECHNIQUE			X
BLOOD-GASES	O_2 - CO_2 CONTENT		X	X
	ACID BASE		X	X
	PERCENT OXYHEMOGLOBIN		X	X
GAS DIFFUSION	CO DIFFUSION CAPACITY		X	X
	O_2 DIFFUSION CAPACITY			X
DISTRIBUTION OF VENTILATION AND PERFUSION	CO_2 AND RQ IN SINGLE EXPIRATION	$\underline{X}$	$\underline{X}$	X
	RADIOACTIVE TECHNIQUES			X
REGIONAL FUNCTION	BRONCHOSPIROMETRY			X
	RADIOACTIVE GAS			X

TABLE I (CONTINUED)

FUNCTION	METHOD	INFLIGHT	PRE-, POST-	ELUCIDATION OF IMPAIRED FUNCTION
LUNG MECHANICS	AIRWAY RESISTANCE		X	X
	FLOW VOLUME		X	X
	BODY PLETHYSMOGRAPH			X
PULMONARY RESPONSE TO EXERCISE	GAS EXCHANGE	X	X	X
	VENTILATION	X	X	X
	DYSPNEIC INDEX	X	X	X
	RESPIRATION RATE	X	X	X
	O_2 PULSE	X	X	X
	BLOOD PRESSURE	X	X	X
	HEART RATE	X	X	X
	CARDIAC OUTPUT			X

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NUTRITION

STATEMENT OF PROBLEM

The success of any manned mission depends upon the availability of a nutrient supply adequate to maintain normal physiological and psychological functioning in the environment of space. The consequences of a failure to do this are well known and run the gamut from mild forms of anorexia (loss of appetite) through decreases in mental acuity to the fullblown symptoms of starvation.

The task of providing a nutrient supply in space must be approached along two major routes. One of these is concerned with determining nutrient requirements while the other is concerned with providing suitable foods to meet these requirements within the constraints of the spacecraft. These tasks are conventionally considered to lie within the purvues of the disciplines of nutrition and food science respectively.

According to the Council on Foods and Nutrition of the American Medical Association, the science of nutrition can be interpreted to apply narrowly to a knowledge of food requirements or so broadly as to include all metabolic processes (1,2). It is particularly difficult to define limits in the mandate for nutrition research when various programs in the biological sciences interface. In this discussion, the scope of nutrition is considered to range from the definition of dietary requirements to the investigation of the role of nutrition in the pathogenesis and correction of certain metabolic aberrations which may be associated with spaceflight. The operational requirements and procedures for the preparation and consumption of food inflight is contained in the section on Food Management.

The end item of all nutritional research in this context will be complete and accurate knowledge of what to feed a man to insure optimum performance throughout a mission of any given duration and indefinitely thereafter.

The second essential task to be accomplished in meeting the nutrient requirements of man during extended spaceflight, is the incorporation of his nutrient requirements into the design of suitable flight foods. Although ideally this task would be delayed until after all requirements are known, it is essential in practice to design foods according to established requirements and then to test and modify these foods as new requirements become known and as other considerations dictate. The process is necessarily an iterative one based on the best current estimates of a set of requirements whose absolute values are indeterminable.

PAST MEDICAL APPROACH

The early manned flights of the U.S. and U.S.S.R. were short and did not require the storage of complete meals. During these flights the feasibility of eating solids and liquids in a weightless state was tested and no problems were discerned which were not adequately met by means of proper packaging. The tubed foods of Project Mercury were similar to those previously developed for Air Force pilots for use during high altitude flights. These foods consisted of pureed meats, vegetables and fruits packaged in collapsible aluminum tubes. The food could be squeezed directly from the container into the mouth. Bite sized foods were also tested during the Mercury flights. These were solid foods processed in the form of compressed cubes which could be rehydrated by the saliva in the mouth. Foods such as cinnamon toast, sandwich sections, compressed confections of various kinds and cereal were provided in this form. In most cases they were coated with an edible gelatin or high fat material to control stickiness and greasiness and to prevent crumbling. These foods were vacuum packed in a container made of four-ply laminated plastic film to protect them from moisture, loss of flavor, oxygen invasion and microbial spoilage (3,4,5,6).

Dehydrated foods were introduced during the Gemini Program. These foods were rehydrated within their own containers to prevent leakage of solid contaminants into the cabin atmosphere. Each individual food package was fitted with a one-way spring activated water injection valve at one end and a folded eating tube at the other. In this type of container, freeze dried foods could remain stable for long periods of time. These foods were rehydrated and squeezed directly from the container into the mouth. After the food was eaten, a germicidal tablet was added and mixed with the residual food to inhibit microbial spoilage (4,7).

Foods used on Apollo are similar to the bite-sized and rehydratable products used during the Gemini missions. Additional items have been added to increased the acceptability and the variety of the menus. The Apollo spacecraft is equipped to provide either hot or cold water for reconstituting the foods and beverages. During Apollo, each astronaut is furnished a total daily intake of about 2200 Calories. This food is made up of about 20% protein by weight, 62% carbohydrate, and 18% fat (8,9).

Theoretical considerations (13,14) and experience under simulated spaceflight conditions indicate that present flight foods are satisfactory for the purposes intended (10, 11,12).

The development of flight foods has not yet taken into account any special nutrient need imposed by the stresses of spaceflight with the exception that certain items have been fortified with calcium to counteract its apparent mobilization from the bones (15). This particular expedient was not based on proven nutrient interrelationships (16), but it nevertheless provided a clear example of the role that nutrients should be expected to play in counteraction of metabolic problems caused by weightlessness. A variety of medical anomalies have been detected in space crews in addition to calcium imbalance and bone demineralization (6). Many of these may be amenable to control through the diet. Although several projects are underway to investigate nutrient relationships with respect to these problems, the predominant effort remains directed towards the maintenance of calcium homeostasis (22,23).

Food in Apollo has been a critical factor in the maintenance of water balance since food has been used to dilute the intense disagreeable flavor of the spacecrafts' water supply.

PRESENT MEDICAL POSITION

The quantities required of different dietary materials are presently unknown and await the establishment of caloric and nutritional requirements under simulated or actual spaceflight conditions. It is estimated, however, that each crew member will require about 2500 calories per day and that 45% of this caloric requirement will be provided by carbohydrate and 45% by fat. In addition protein nitrogen will be supplied at about 0.6g/kg body weight.

Ground based simulator studies have shown that current flight foods and feeding systems are acceptable and adequate for periods of at least 60 days. It has generally been found that the palatability of the foods increases to a desirable level after the first few days of familiarization. These foods have not been implicated in altered behavioral patterns of performance levels compared to matching fresh type foods. However, under confinement conditions these diets have been associated with negative nitrogen and mineral balances. In spaceflight, decreases in bone density, loss in red cell mass, and a variety of other problems have been detected in which the food supply could be implicated in either a synergistic or antagonistic role.

The inflight food supply must be designed to alleviate some of the emotional stress characteristics of spaceflight. This in turn will help reduce negative metabolic balances.

At the present time it is not known how long current flight foods could be safely used. The required testing of these foods under simulated spaceflight conditions has not been conducted for periods greater than sixty days. Reliable information is not available to predict nutrient needs in spaceflight of extended duration so that no evaluation of present flight foods can be made on this basis. Even if today's flight foods satisfy long term ground-based requirements, they still cannot be considered suitable for flights of extended duration. These flight foods have not been designed to meet precisely defined nutrient requirements and undoubtedly incorporate large excesses of several nutrients in less than optimal combinations. In the provision of food supplies to crews of short term missions, it has been more critical to properly package and preserve foods than to insure optimal nutrient intakes.

FUTURE EFFORTS

The presiding assumption underlying this discussion is that currently planned missions will utilize a food system consisting entirely of processed, stored food and that water will be largely recycled. The extent of the research effort necessary to regenerate consumables other than water and oxygen excludes their consideration at the present time. Nevertheless, it is acknowledged that at some future date there will be missions in which a completely stored food supply will not suffice and in which it will be more expedient to recycle some constituents. For this reason, research and development in flight feeding systems should take into account the eventual emergence of a capability to supply basic nutrients through the recycling of organic wastes.

The primary requirement for a stored food supply after optimum nutrition is assured, is for it to have minimum mass and volume. In achieving this objective the following conditio must be satisfied:

(a) Nutrients must be provided in precise accordance with their expenditure at the level of performance and psychological well-being desired.

(b) Foods must be designed in a manner which will insure complete consumption and digestion of all nutrients.

Determination of Requirements

The task of specifying the optimum composition of space foods differs from the type of work previously performed in the establishment of nutritional requirements. Because of the large variations among different investigators, it is not possible to rely on present estimates of minimum requirements. Moreover, the recommended dietary allowances (30) are even less useful since they are statistically formulated to encompass the population and to include an arbitrary safety factor. The present task demands that requirements not only be established with a precision never before necessary, but also that this be done, insofar as possible, on an individual basis. Space crews are small in number and individual variations in nutrient requirements are known to be large. With respect to the major nutrients, substantial weight savings could be realized by providing for an individual's needs and excluding allowances for population variation and measurement uncertainties.

In the attainment of the above objectives the following specific areas of investigation are considered essential (18,19,20,21,26):

(a) Minimum protein content

The minimum protein requirements of men under the stress of simulated spaceflight must be determined. These studies should be confined to proteins of accepted good quality and will not pursue the potential additional advantages of manipulating amino acid mixtures. Experimentation must be conducted over a sufficiently long period of time and with sufficient numbers of subjects to enable estimates of variability to be made and extrapolations towards long duration missions to be reliable. The work will be expected to refine current estimates of minimum protein needs and to determine the effect on these needs of long-term stress. In addition this work will contribute to the urgent need to develop methodology for accurately estimating an individual's nutritional needs. Although, during the development phase, this methodology may involve animal experimentation and a variety of complex clinical procedures, the final technique for determining an individuals' nutritional needs must not itself demand metabolic balance experiments or surgical intervention of any kind. The methodology must be rapid and reliable and of a kind that can be applied to the prospective spacecrews themselves.

(b) Maximum caloric density

Efforts must be undertaken to determine the minimum mass of a carbohydrate and fat combination which will satisfy the energy demands of metabolism imposed by the mission profile and which will be compatible with optimum health and performance. This minimum mass would theoretically consist of a diet containing no carbohydrate. Since metabolic problems associated with a very high fat diet preclude this possibility, the task becomes one of refining current recommendations. The guideline developed to govern the fat content of flight foods must be responsive to individual requirements and the need to insure optimum palatability. For purposes of this type of investigation, data on the energy demands of spaceflight must be accumulated and precisely provided for by the major caloric components of the diet.

(c) Vitamins, minerals and essential fatty acids

Since the vitamins, minerals and essential fatty acids are not required in large amounts, no significant weight saving would be realized by attempting to provide for an individual's needs. It would appear merely necessary to develop and test a uniform allotment of these constituents and to insure that the metabolism of the micro-nutrients occurs under spaceflight conditions as it does normally. Thus the micro-nutrient allotment will be based upon re-examination of existing knowledge and the results of such research as is necessary to confirm and refine present allowances. Owing to the fact that human requirements of trace minerals and accessory nutritional factors may not be completely recognized, it is necessary to unequivocally test purified nutrient mixtures for periods of time which last at least as long as a projected flight. In this phase of investigation it will be necessary to directly measure the vitamin and mineral titres of the biological fluids in order to detect deficiency states and permit objective evaluation of the absorption and utilization of vitamins.

(d) Physical and Chemical basis of palatability

It is necessary to identify the minimum physical and chemical requirements for the formulation of a palatable and psychologically satisfying diet that will insure complete consumption for the proposed duration of the mission. This work will yield the specifications for flavor components, physical form and meal variety. The diets envisioned for use during prolonged missions will be considerably simpler in chemical composition than those utilized in spaceflight today. It is not intended to advance the merits of a purified diet at this stage or to counter arguments that, in prolonged use, such diets are necessarily monotonous and pose grave psychological dangers. What is proposed is the formulation of a diet which is acceptable in every way. A large variety of natural foods is usually the regimen advocated to insure optimum nutrition. Such a regimen however must be analyzed and its essential characteristics identified. The diets used in prolonged spaceflight should be only as complex as they need to be. The necessity for diets of defined nutrient composition stems from the intractability of providing a minimum mass of nutrients in approximate accordance with expenditure through the use of a variety of natural foods of extreme complexity and variable composition.

(e) Dietary preconditioning

Studies of dietary preconditioning should be conducted to assess to what extent previous dietary intake can affect future requirements. For example, it is well known that such treatment can markedly influence the interrelation between fat and carbohydrate metabolism (24). However, this preconditioning does not necessarily consist of prolonged preflight adaptation to the flight foods themselves. Such adaptation may be undesirable as the flight foods will be so specialized as not to be good nutrient sources under ground-based conditions.

(f) Water

Although the recycling of water is anticipated, the determination of its requirement under simulated conditions must be made in order to insure that sufficient water is consumed. This is particularly pertinent in view of the losses in weight and plasma volume observed in past missions and the possible failure of the thirst mechanism to indicate this requirement to the spacecrews (17,25).

Since dehydration is rapidly debilitating, the determination of water requirements and the state of dehydration under spaceflight conditions is urgent for space missions of any duration.

(g) Assessment of nutritional and metabolic status

An integral part of the establishment of nutritional requirements and the testing of flight foods is the recognition of flight related metabolic problems at an incipient stage. In order to identify these problems, techniques must be employed to accumulate that inflight data which will most accurately describe the dependence of metabolic functions on time-in-flight. Accurate base-line data and estimates of variability will be obtained in ground-based control studies. This area of investigation should be given the highest priority in order to insure that as much data as possible is obtained from forthcoming flights of short duration. Broader interpretation of the limited metabolic samples that can be obtained from astronauts is essential if prolonged animal experimentation on the metabolic problems unique to spaceflight is to be avoided.

The principal purpose of this research is to develop specific tests, techniques and procedures for a relatively easy, quantitative determination of the metabolic state and health of an astronaut and early recognition of potential problems not revealed under simulated conditions.

This investigation must include the following tasks:

(1) Chemical analysis of blood, urine, sweat, feces parotid fluid and hair should be made. From this it follows

that the preservation and collection of metabolic samples must be assured. The availability of these vital sources of information adds immeasurably to the interest of the scientific community in manned experimentation in space.

(2) Physical measurement should be made of metabolic rate, body weight, specific gravity, lean body mass, skin-fold thickness, skeletal density, and muscle size. At an early stage it is essential to use this data to assess the transfer or carryover validity of results obtained under simulated spaceflight conditions.

(h) <u>Nutrient interrelationships</u>

The role of nutrition in the amelioration of metabolic problems recognized in flights of short duration or anticipated in flights of long duration should be investigated. The relationship must be established between nutrient composition and the medical anomalies noted in spaceflight. The nutritional route provides ready and convenient access to the control of problems generated by harmful encounters of the human with his environment. The degree of dynamic control available at this point must be well known to the mission monitors so that nutrient intakes may be regulated accordingly.

(1) Calcium balance and bone demineralization is a problem in which this control has already been attempted and is an area which demands further study. It is not necessarily true that the negative calcium balances previously noted are evidence of calcium deficiency and that losses of bone can be corrected by

calcium feeding (16). In fact, the administration of a high calcium diet may accentuate hypercalcinuria and increase the danger of kidney stone formation. In attempting to achieve mineral balance and skeletal stability, the emphasis should be placed on other dietary components such as protein, phosphate, magnesium, fluoride and strontium.

(2) Potential spacecrews should be fed diets with a minimum potential for causing fatty deposits in the arteries (atherogenesis). In the age group to which the astronauts belong, the development of cardiovascular disease ranks high among the probable causes of incapacitation during prolonged spaceflights. Flight foods should be evaluated and if necessary modified so that their consumption will result in low serum lipid concentrations. Also the development of flight foods should be responsive to the emergence of additional meaningful knowledge in this area.

(3) Consideration should be given to the maintenance of dental hygiene and diets should be designed to minimize the occurrence of tooth decay and other difficulties (27). Cognizance must be taken of the predominant physical form of the food and the type and concentration of tis carbohydrates.

(4) The relationship between nutrition and infection (31) must be recognized in the design of flight foods. Infective processes which arise inflight should be countered by good nutrition and the flight feeding system should be adaptable to the changing needs imposed by such occurrences.

(5) An additional area of vital concern includes the relationship between diet and radiation protection.

Development of Flight Foods

Research on the development of flight foods must proceed concurrently with the establishment of nutritional requirements. The development of suitable foods for advanced feeding systems cannot be delayed until the establishment of requirements as these foods must be versatile enough to respond to dynamic nutritional needs. The approximate composition of any formula-type diet is well known but it is the quantitative nature of this diet which must await the results of extensive research into nutritional requirements and the application of this research to particular individuals.

Ideally, foods developed for extended space missions should be evolutionary products of those used on previous flights. This ideal must be tempered by the realization the simplified flight foods have not been developed based upon complex nutritional research (28). These food systems have instead been impressive displays of modern food technology and cannot be considered as compositional prototypes for long duration missions.

(a) Analysis of present flight foods

Since the interpretation of all biochemical, physiological and microbiological studies inflight and under simulated conditions depend upon accurate knowledge of nutrient intake, it is necessary to rigidly characterize the available nutrient composition and storage stability of present foods.

(b) New flight foods

(1) Foods must be developed which are highly digestible and contain only sufficient indigestible residue as is necessary to insure compatibility with gastrointestinal function and waste management systems.

(2) The relationship of the foods to the characteristics of the intestinal flora must be defined and manipulated as required.

(3) A modular food concept must be exploited in which only a few basic items need to be consumed to provide a complete food and in which there is sufficient flexibility to meet changing requirements if inflight monitoring so dictates. It should be possible to manipulate the basic food materials and flavor ingredients in differing combinations and physical forms to satiate all requirements for variety in flavor and texture. Linear programming techniques must be developed to solve the complex dietary problems presented by a dynamic set of requirements.

(4) It is necessary to conduct research on the optimization of feeding schedules. The advisability should be assessed of instituting more frequent feeding periods to optimize the efficiency of food utilization. The rhythmicity of bodily function might have great significance in this regard and its role should be used to full advantage (29).

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THERMOREGULATION

STATEMENT OF THE PROBLEM

There is no reason to suspect that space flight will directly affect the physiological mechanisms of temperature regulation. However, the space environment differs from the earth environment in a number of factors, and these factors present problems in thermoregulation.

Weightlessness

The lack of a gravitational field in space means that normal convection, as experienced on earth, does not take place. This means that artificial circulation of air must be provided in the case of a shirtsleeve environment, which in turn presents problem in calculating the heat removal values. Forced convection at low velocities is difficult to analyze because of the variance in velocity from one surface to another on the body.

Reduced Atmospheric Pressure

The reduced pressure of the spacecraft atmosphere also results in a reduction in the convective heat removal capacity of the gas. This is counteracted in some degree by the cooling effect resulting from the evaporation of water from the body, assuming a given humidity under reduced atmospheric pressure.

Atmospheric Composition

From the point of view of thermoregulation, the particular constituants of the atmosphere (exclusive of water vapor, which is discussed above) are important in determining the specific heat and the conductivity of the convective coolant.

Humidity can also be a factor affecting thermal comfort. Low humidity can cause discomfort unrelated to ambient temperature. It can dry the skin, cause burning of the eyes and dry the oral and nasal mucosa thus increasing the susceptability to respiratory infection. The low total pressure in a spacecraft increases the rate of evaporation, aggravating the effects of low humidity.

If thermal comfort is not maintained in the space vehicle astronaut performance will be reduced and the very advantages in having a man aboard a spacecraft will diminish accordingly. This decrement is first apparent in the performance of low motivation tasks. It becomes more pervasive as the duration and intensity of discomfort is increased.

The Pressure Suit Environment

The EVA and Lunar operations pressure suits must be well insulated to protect the crewman from the extreme temperatures of the space environment. The effectiveness of this insulation is such that all of the heat produced by metabolism in the man must be removed by a coolant system in the suit. Because of the relatively high metabolic rates predicted for pressure suit operations, failure or inadequacy of the coolant system can quickly lead to intolerable thermal conditions in the suit.

PAST MEDICAL APPROACH

The past approach in maintaining a comfortable environment within the spacecraft has been to prescribe a temperature range of 75° ± 5°F. with a relative humidity from 40% to 70%. During the Mercury and most of the Gemini flights the crewmen were partially dressed in a ventilated pressure suit so that off-nominal changes in the cabin environment would not become critical. In addition, the available habitable volume severely limited astronaut activity and rendered metabolic rates and heat production very predictable. Under these conditions there has been no thermal problem while the environment remained within the prescribed limits. The 40% relative humidity limit at 70°F. allows a minimum humidity of 7.5 mm Hg water vapor pressure. This is not an extremely low humidity level, but in combination with the low ambient pressure inside the cabin could have contributed to the eye irritation and nasal congestion experienced during some Gemini flights.

In the past, the metabolic heat produced under suited conditions was removed by ventilating the pressure suit with dry oxygen at 11 cfm and by increasing this ventilation up to 26 cfm during EVA, since higher metabolic rates were expected. When gas cooling is used in the pressure suit the majority of the heat is removed by evaporation of sweat. Therefore, when gas cooling is used to support high metabolic rates the sweat rate requirements become unacceptably high. Gas cooling proved to be inadequate during Gemini EVA missions where actual metabolic rates were higher than those predicted. Heat stress was experienced, resulted in premature fatigue and contributed to the shortening of several EVA missions.

PRESENT MEDICAL POSITION

To insure adequate astronaut performance, the astronaut thermal environment must remain within preset limits for both comfort and tolerance. The design criteria that have been adopted utilize a mathematical model with inputs for all of the physical variables that effect heat transfer of man with his environment. This model has been combined with a mathematical model of thermoregulation in man. The combined models allow a prediction of steady state body heat storage for any combination of environmental variables and heat production rates in combination with environmental variables and heat production rates in man. A limit of $\pm$ 65 BTU heat storage in the model has been set as the comfort range. The extremes of recognized empirical comfort limits for earth conditions predict heat storage of this magnitude when the conditions of the empirical testing are applied to the models. For an earth shirtsleeve environment the maintenance of $\pm$ 65 BTU heat storage requires temperature control of $\pm$ 3° or 4° F. The required range of control depends on the environmental variables and the metabolic rate.

Figure 1 shows the required comfort envelope for an orbital workshop environment derived by the use of the comfort criteria. The comfort envelope defines environments which will insure comfort for crewmen in the orbital workshop working at predicted mission rates. Comfort envelopes of this type can be generated for missions in which different breathing gases or different pressures are used, or where individual wind speed control or individual insulation control are not available.

For metabolic rates above resting, the comfort point has been raised linearly to 130 $\pm$ 65 BTU at 2000 BTU/hr. This is based on maintaining the crewmen below the sweating threshold at the higher metabolic rates. It should be emphasized that the comfort heat storage limits refer to heat storage in the thermoregulatory model. Heat storage could not be measured accurately enough in a man to determine the state of comfort, particularly in view of the fact that different individuals have different temperature setpoints, and circadian rhythms appear to affect these setpoints. In addition to heat storage limits, the design criteria limit the cabin environment by imposing maximum and minimum atmosphere, surface and mean radiant temperatures.

The heat storage tolerance limits are ± 300 BTU/hr. These limits are based on resting heat tolerance tests in the literature and may be conservative at high metabolic rates. It is a well known fact that the core temperature seems to be physiologically elevated during high work rates; that it is elevated even in a cool environment. At the same time, if a cool environment is provided, the skin temperature will drop considerably and if a man is maintained on the threshold of sweating as with a liquid cooled garment, there will be very little total heat storage in the body, even at high metabolic rates. The point that is not clear is whether a high metabolic rate increases heat storage tolerance or simply enforces operation closer to the tolerance limit.

The present approach to maintaining a man within comfort and tolerance limits in a pressure suit is to use a liquid cooled garment (LCG) with a three position manual temperature control. The manual control will require attention by the crewman to maintain a suitable thermal environment. On first use of an LCG there is a tendency to avoid use of the coolest setting. This tendency is overcome after experience has been gained with the LCG.

The present position on the minimum humidity in the spacecraft is based on the following considerations: Although at sea level conditions subjective discomfort is not noticed above water vapor pressures of 5 to 6 mm Hg, there is evidence that the functions of the mucous membranes in the nose and throat are impaired at water vapor pressures below 8 mm Hg, with increased likelihood of respiratory infection. The experience obtained in long duration Gemini flights indicates that there are factors in the spacecraft environment that accelerate drying of the mucous membranes in the nose and throat. In light of these considerations, a minimum of 8 mm Hg water vapor pressure has been established.

FUTURE EFFORTS

Future efforts in improving the ability to maintain crew comfort will be directed to improving models of heat transfer and thermoregulation in man, so that comfort limits can be more accurately predicted, particularly during transient metabolic rates and during high work rates.

A comprehensive tolerance testing program is required to better define heat tolerance limits at high metabolic rates in terms of some physiological parameter such as heat storage.

A testing program is also required to evaluate the effect of reduced pressure on the tolerance to low humidities and to define lower limits of humidity both for steady state and transient exposures.

The development of an automatic control system to regulate the water temperature in the liquid cooled garment would eliminate the attention that the manual control requires of the crewman and would avoid the possibility of the crewman failing to make appropriate control action or making inappropriate control action as a result of incapacitation or any other reason. A manual override feature, however, should be provided.

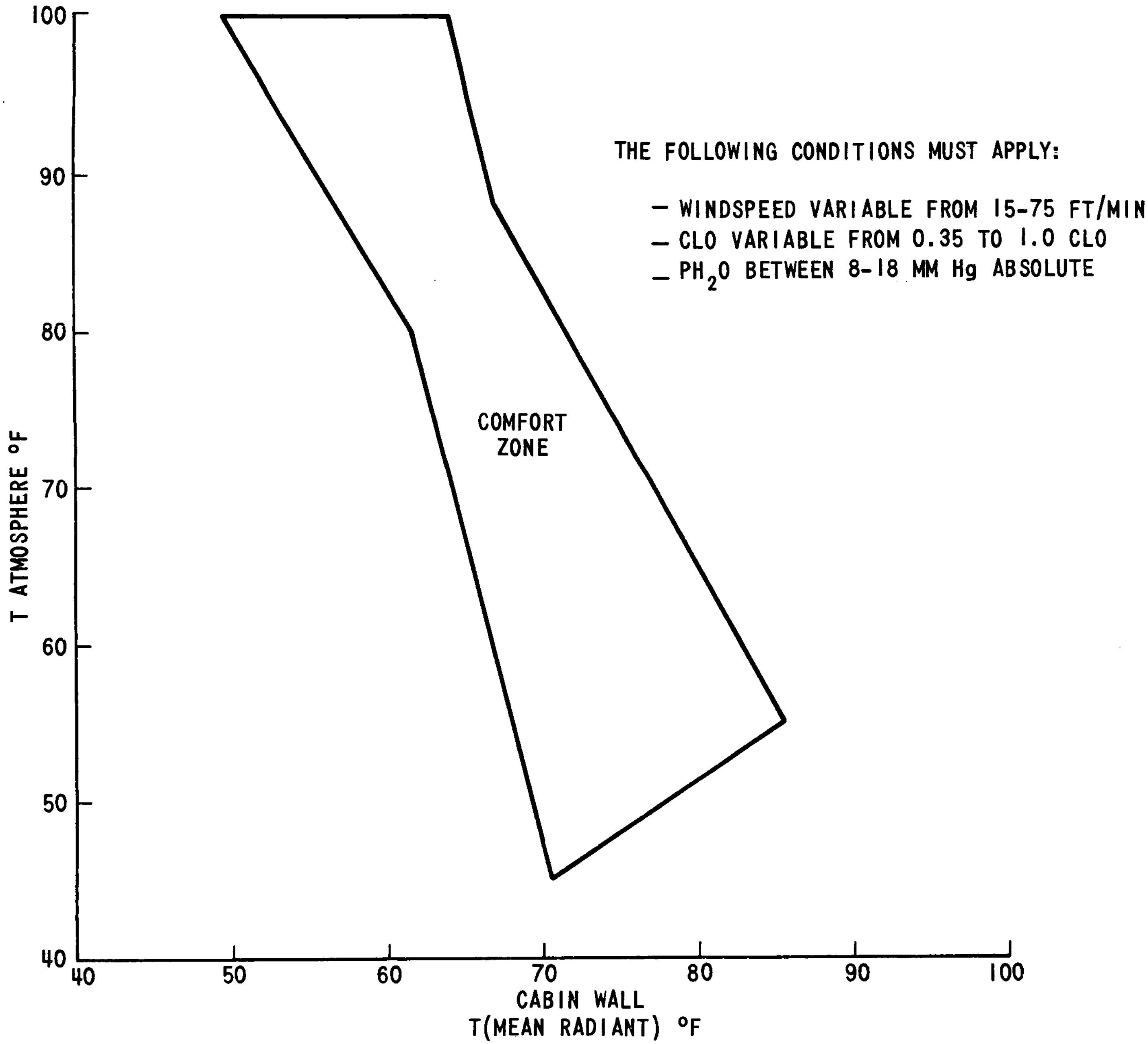

FIGURE 1 - COMFORT ENVELOPE FOR ORBITAL WORKSHOP MISSION

WATER MANAGEMENT

STATEMENT OF THE PROBLEM

The major water management problem that must be solved before long duration missions can be realistically planned and programed is that of potable water recovery from wastes. The logistics of space travel necessitate the reclamation of potable water from urine, wash water, condensate water, and possibly feces. Potable water must be reclaimed at a rate sufficient to sustain the crew of a multimanned spacecraft during extended space flights.

Of the three life support consumables (water, oxygen, and food) to be regenerated, water is required in the greatest quantity, about 70 percent by weight, Figure 1, and is the easiest to reclaim. All waste conversions must be within the prescribed engineering constraints of adequate performance and reliability in the spacecraft environment which consists of a reduced atmospheric pressure and zero gravity. In addition, the psychological factors of crew acceptance must be considered, particularly with regard to the taste, odor, and appearance of the potable water produced from wastes.

Bioengineering capabilities must be developed to a point where the regenerative life support system is capable of providing for the physical collection of reclaimed water and for maintaining and controlling all chemical and biological contaminants and pollutants capable of degrading the wholesomeness of the potable water. In addition, this system must be capable of providing temporary storage facilities, and a reliable and sanitary potable water delivery system.

During an extended flight, abnormal variations in the chemical composition of the astronauts' urine may occur, either in response to the rigors of extended space flight or as a result of illness. Consequently, a monitoring device may be required (a) to detect significant variations in the composition of urine (for example, the presence of any toxic constituent which would not be removed during inflight water reclamation) and (b) to segregate or reject abnormal urine in order to prevent its being recycled through the regenerative life support system and affecting the other crewmen.

PAST MEDICAL APPROACH

During the Mercury and Gemini programs and because of the limited duration of the flights, a sufficient quantity of water was easily stored on board the spacecraft before launch, thus limiting the medical responsibilities of water management. However, the medical responsibilities are extended somewhat during the Apollo Program. The water supply subsystem of the Apollo command module manifests the first inflight water reclamation (i.e., the recovery of potable water from the byproduct of fuel cell operation). The nominal fuel cell water production of 1.5 pounds per hour is transported, preferentially, to a storage unit for potable water (to sterilize this water, sodium hypochlorite is added daily) or, secondarily, to a storage unit for water used as the evaporant for spacecraft cooling. If both units are filled, the excess water is vented overboard.

PRESENT MEDICAL POSITION

The water system must deliver 6.5 pounds/man-day of potable water for human consumption with an additional 3.5 pounds/man-day required for personal hygiene. To date, all medical research on the toxicity of potable water recovered from liquid wastes has been evaluated on the basis of requirements established by the U.S. Public Health Service. In general, present medical and bioengineering research is being, or must be, directed towards the resolution of the following areas:

(a) The development of effective and reliable waste water collection devices.

(b) The establishment of realistic criteria or standards for the required quality of potable water recovered from liquid wastes.

(c) The development of water reclamation systems capable of reclaiming water that meets these criteria from urine, wash water, condensate, and feces.

(d) The selection of effective water sterilization techniques that are compatible with the spacecraft systems as well as with man. Compatibility must be achieved with other equipment that will use the water, such as the electrolysis equipment for oxygen generation, as well as minimizing corrosion and degradation possibilities.

(e) The development of monitoring capabilities to insure compliance to medical requirements.

FUTURE EFFORTS

Future, extremely long-duration flights will dictate more complex requirements for water recovered from wastes. The water used in long-duration flights will be recycled through the human system many times during the course of the flight, providing an opportunity for continuing concentration of trace materials. Greater stringency in requirements, particularly with regard to biological quality, is needed to maintain requisite wholesomeness in these circumstances. These requirements are:

(a) Standards — Provide for the establishment of Flight System Qualification Standards having microbial, chemical, and physical parameters. These flight standards will include a list of medically acceptable limits of constituents commonly found in water and limits of containments peculiar to the particular source of water under consideration.

(b) Monitoring systems — Provide for the development and evaluation of a monitoring system capable of measuring flight standards applicable to space flight. These standards will be indicative of the water quality as well as source and/or water system malfunction. Provide for the development and evaluation of a water volume intake monitoring system.

(c) Microbiological control — Provide for the development and evaluation of microbiological control procedures compatible with all water systems which will insure that potable water biological requirements are met during an extended space flight. Conduct research to determine the interrelationship of water, sterilants, and spacecraft water system materials.

Several physical and chemical techniques for water reclamation are being considered; these include: (a) vacuum distillation, (b) freeze drying, (c) electrodialysis, (d) ion-exchange processes, (e) activated carbon absorption,

(f) membrane permeation, (g) vapor pyrolysis, (h) combustion, (i) electrolysis, and (j) vapor compression. The most promising approach to potable water reclamation techniques appear to be either vacuum distillation or vapor compression with pyrolysis.

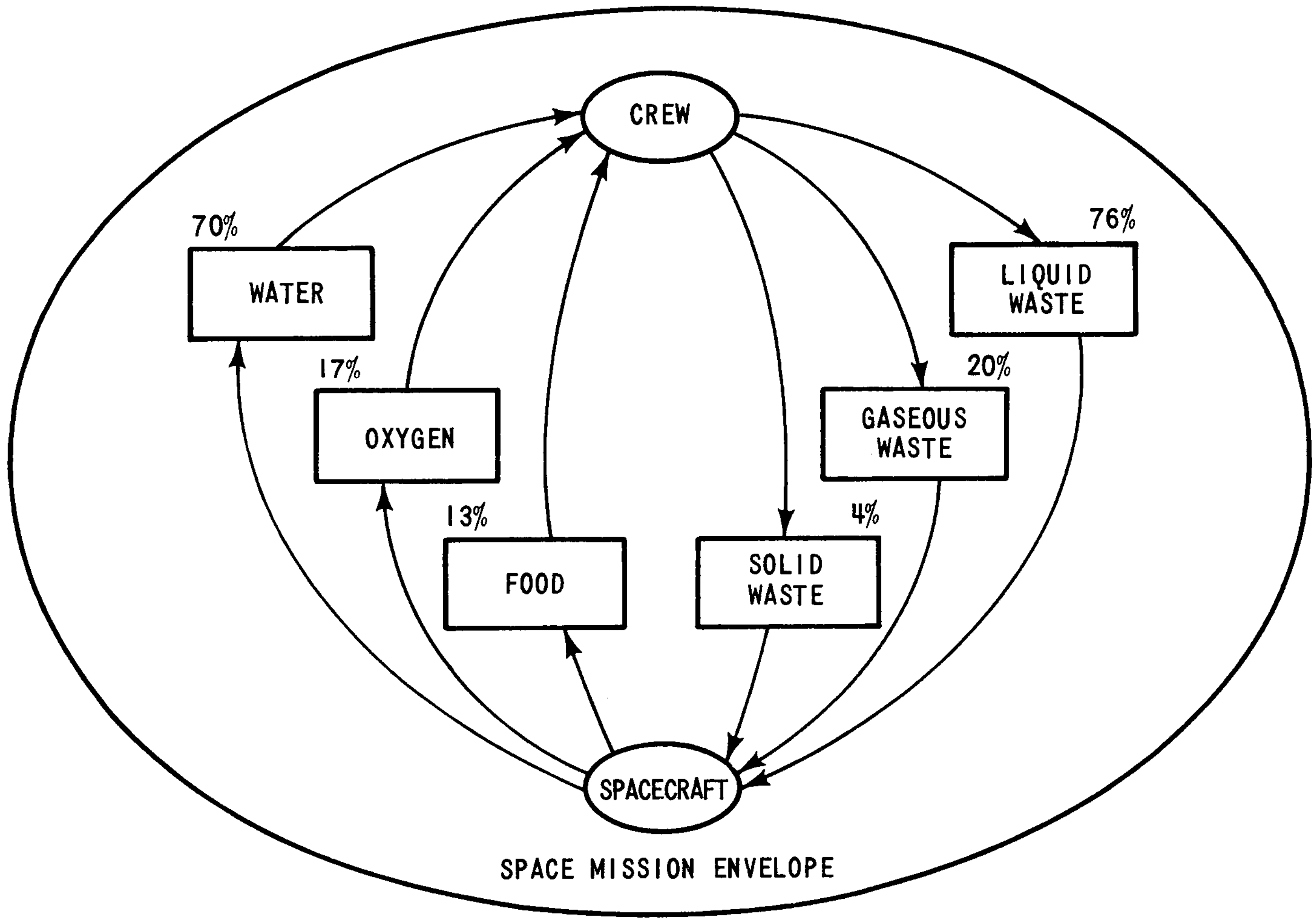

FIGURE 1 - THE INFLIGHT CLOSED ECOLOGY

WASTE MANAGEMENT

STATEMENT OF THE PROBLEM

During extended space flight, the crewmen must be provided with efficient and acceptable means for collecting, sampling, processing, and disposing of all body wastes generated, specifically urine, sebum, feces, vomitus, mucus, hair, nails, and food residue. The spacecraft waste management system developed to accomplish these tasks must transport the collected liquid wastes to the water management system for reclamation. The system must also provide waste samples (either aliquots or whole) for inflight food reclamation experiments, biomedical monitoring and for postflight biomedical analyses. Auxiliary components of the waste management system are to be used for disposal of consumable personal hygiene items. (The requirements for the personal hygiene equipment are described in the section on Personal Hygiene).

PAST MEDICAL APPROACH

Because of the limited duration of previous space flights, waste management was primarily concerned with the collection and containment of biological wastes. The waste management system of the initial Mercury flights had two components: a simplified urine collection device consisting of an in-suit urination bag, and a bag for vomitus. For Mercury 9, a transfer assembly and a storage bag were added to the urine collection device. No fecal subsystem was required.

For both the Gemini and Apollo missions, the following waste management system was used: a urine transfer assembly with overboard dump, a defecation bag, and a vomit bag (two for each crewman). Urine sampling and volume measurement occurred only on Gemini VII and Gemini IX. No fecal sampling ever occurred; instead, the feces were treated with a germicide and stored.

PRESENT MEDICAL POSITION

The waste management system described in the previous section, although adequate for the relatively brief missions of Mercury, Gemini, and Apollo, is patently unsuitable for future extended missions. Although no space qualified waste management system currently exists, many of the requirements and constraints for an adequate system have been determined, and prototypes have been developed.

One of the most essential requirements of a waste management system is to prevent environment contamination during collection, processing, and disposal or storage of waste and waste samples. No buildup of toxic gases, odors, and/or micro-organisms can be tolerated. Thus, the system must: (a) be physically isolated from the living quarters; (b) include auxiliary equipment to isolate odor, gas, and aerosol from the remainder of the vehicle; and (c) remove odor from the latrine area within 5 minutes. In addition, components of the system must interface, without contamination, with the water management system.

The urine/fecal collection subsystem must provide for the aesthetic collection of biological waste material and must be based on normal human physiological principles and familiar habits. No direct contact between man and the collection equipment, such as condoms or adhesive devices, can be involved. Moreover, the urine/fecal collection system should be compatible with the disposal of other body wastes (except keratinized waste products such as hair and nails) and food residue. To collect keratinized waste products, separate or auxiliary devices operational in zero gravity are required. The simplest system involves a vacuum cleaner with subsequent disposal of the wastes.

To satisfy experimental and biomedical monitoring objectives, provisions for accurate (± 1 percent) measurement of urine and fecal mass and/or volume are required on a routine basis. Periodic sampling for later ground-based analyses should also be available. The sampling method must provide adequate sample identification, preservation, and compatibility with spacecraft restraints. Periodic samples of keratinized wastes may also be required; hair and nails are potentially simple sources for ascertaining protein and trace mineral status. The keratinized wastes need not be collected for reclamation experiments since ground-base data on the major nutrient balance contributions indicate these constituents are insignificant.

Several methods of treating, processing, and disposing of body wastes have been investigated. These studies show that the storage of raw, wet feces by freezing or holding in heat-sterilizable pressure tanks for extended periods is not practical; not only are the wastes needed for water reclamation but chemical changes unacceptable for postflight medical evaluation occur during storage. However, a requirement for freezing small fecal samples may be established for postflight virus and hormone analysis studies.

Storage of body wastes in a dry state offers distinct advantages for biomedical monitoring and experiment programs since microbial decomposition of waste is prevented. In addition, the equipment used to dry the wastes could be modified to provide reclaimed water.

Body wastes not required for experiment or biological monitoring, or that are too impractical for use as sources for water reclamation could be incinerated or dumped overboard. Currently, the dry waste storage method, because of its simplicity, versatility, and adaptability to water reclamation schemes, has been chosen for use.

A complete urine/fecal collection device and associated equipment including the dryer should not require more than 5 cu ft; the power requirement should not exceed 10 W-hr per man-day.

The waste management system and its associated biological monitoring facility must be integrated into the vehicle to minimize crewtime for operation and to separate the space "bathroom" from the food preparative area. Medical, human factors, and engineering personnel must work closely together during design and development of waste management systems to insure that crew acceptability is attained and that the required biomedical information is retrieved.

FUTURE EFFORT

Both ground-based and inflight evaluation and verification of proposed waste management systems must be conducted. The ground-based studies conducted in simulated space environments, will include an examination of the reliability and suitability of using keratinized wastes to determine nutrient status. Inflight studies will include evaluation of other waste management systems such as wet oxidation, electrolytic waste treatment, and biological waste treatment. In addition, an inflight monitor capable of detecting microbes in the spacecraft atmosphere must be developed.

PERSONAL HYGIENE AND CLOTHING

STATEMENT OF THE PROBLEM

The basic problem of the personal hygiene program is that of providing the hygienic necessities for crewmen during an extended mission in space. Although the frequency of bathing in Western civilization is much greater than is justifiable for physical health reasons, regular bathing is recommended on long space missions for social purposes and for the individual satisfaction it provides. Sufficient quantities of expendable personal hygiene items (soap, body wipes, bactericides, dentifrice and temporary dental restoratives) must be provided as well as hygiene procedures and equipment which are effective in zero-g. The hygiene equipment (i.e., hair and nail clippers, shavers, and whole-body showers) must be capable of functioning properly throughout the duration of an extended mission in space with minimal maintenance and repair.

Clothing serves the purposes of thermal insulation, skin protection, pocket stowage, and personal hygiene. Much of the skin's excreta (cellular debris, hair, sweat, etc.) is transferred from the body to the clothing, which thus becomes a good transport agent for body waste to a disposal point. Criteria for space clothing, other than pressurized garments, include: comfortable, close-fitting; compatible with space suit; washable or disposable; compatible with vacuum and low temperature, chemically inert; flame, soil, and tear resistant; lint-free, moisture absorbent and transmissible. The clothing ensemble must have sufficient variety (e.g., shorts and long trousers) to accommodate different operational, experimental, and recreational requirements. Color and fit should be satisfactory to the wearer.

PAST MEDICAL APPROACH

Because of the limited duration of the Mercury flights, personal hygiene items were not provided. During the Gemini flights, which were somewhat longer in duration than the Mercury flights, the only personal hygiene items available were wet wipes, dry wipes and toothbrushes. Essentially the same items, with the addition of ingestible toothpaste, are being used on Apollo flights.

In Apollo, a one-piece constant wear garment, similar to "long johns", is worn as an undergarment for the spacesuit and for the inflight coveralls. The garment is porous-knit cotton with a waist-to-neck zipper for donning. Biomedical harness attach points are provided.

During periods out of the spacesuits, crewmen wear two-piece teflon fabric coveralls for warmth and for pocket stowage of personal items. Communication carriers ("Snoopy hats") with redundant microphones and earphones are worn with the pressure helmet; a light weight headset is worn with the inflight coveralls.

PRESENT MEDICAL POSITION

On extended duration missions, a personal hygiene station should include: provision for a daily "sponge bath" plus periodic "whole body showers"-either in a wet suit or turkish-bath enclosure; oral hygiene equipment similar to Gemini-Apollo; spring-wound razors, hair- and nail-cutting devices with collection provision. A general vacuum system for debris removal is recommended.

Clothing should conform to criteria listed above. The question of a "space laundry" facility versus disposable clothing has not been resolved: The relevant trade-offs include weight, power, volume, and astronaut time. The development of flame-resistant paper clothing which can be tightly packaged favors the disposable clothing concept, if astronaut acceptability can be insured.

Lightweight helmets or hats should provide head and eye protection from zero-g activities, communication microphones and earphones, and biomedical monitoring attachment capabilities.

FUTURE EFFORTS

Design and develop an integrated personal hygiene station incorporating:

a) dry and wet wipe cleansing;

b) oral hygiene;

c) whole-body wet-wash (suit vs. turkish-bath enclosure);

d) shaving, hair and nail clipping;

e) vacuum system to contain and collect hygiene debris.

Develop suitable clothing and resolve disposable clothing vs. space laundry trade-off. Pursue development of fire resistant paper clothing. If laundry is designed, integrate with personal hygiene station. Evaluate hygiene and laundry impacts on water requirements for extended missions.

Evaluation of proposed equipment and procedures should be done primarily through ground-based studies including chamber tests, with inflight verification of ground results.

SPACECRAFT ARCHITECTURE

STATEMENT OF THE PROBLEM

As mission duration increases, spacecraft configurations must progress from live-in cockpits to space habitats that provide an environment that approximates the comforts and conveniences of a well-designed laboratory and home on Earth. Indeed, some aspects of the spacecraft should surpass typical on-Earth work and living environments to compensate for enforced confinement and the other stressors of extended space flight.

The habitability features of a spacecraft should not be seen as luxurious frills but as necessary for maintaining peak operational efficiency of a crew over long periods of time. The spacecraft designer must strive to insure the same high reliability in the performance of the astronauts as is demanded in the performance of space hardware. On the other hand, the severe constraints imposed by weight and volume limitations of launch vehicles pose a challenge to the achievement of these goals, so imaginative design and thorough testing of alternative designs is required.

Furthermore, "minimum habitability standards" tend to become maximum standards or design goals. Thus, the establishment of continuing habitability review procedures throughout the design and construction of a spacecraft is perhaps more important than the codification of a rigid set of standards. The standards that are employed must be formulated with due consideration to realistic growth allowances, construction drop-offs, operational conditions, and the continual encroachment which occurs during the development process. Above all, the key to a habitable spacecraft is a sensible integrated design, a functional Gestalt, and this cannot be achieved by piecemeal application of component criteria.

With these reservations in mind, the following broad aspects of spacecraft architecture can be separated:

a) Amount and utilization of spacecraft volume

b) Decor and color

c) Furniture and fittings

f) Mobility and restraint aids

g) Illumination

h) Ambient noise levels

Other aspects of the spacecraft environment (temperature-humidity, atmosphere, waste management provisions, etc.) are considered in separate sections of this document.

PAST MEDICAL APPROACH

The volume per man, duration, and rated impairment effects of American and Russian space flights through Gemini VII, as well as relevant Earth-based situations, are summarized in Table I from Fraser (Ref. 1) and Roth (Ref. 2). Because of the relatively short duration of these flights, the applicability of these data to long-duration mission design is questionable at best. The extraordinary feat of Borman and Lovell, namely, maintaining remarkable performance during two weeks spent in a volume aptly compared to the front seat of a Volkswagen is more a testament to the adaptability and resilience of these astronauts than a design reference point. In any case, there were impairments detected on this flight, primarily physiological changes, but also sleep disturbances, and irritability during the last two days of the mission. The 80 cubic feet of free volume available to these two men probably represents an absolute minimum requirement for the 14 day duration.

The more recent Apollo and Soyuz flights have utilized larger volumes, but still for short durations. However, the "motion sickness" episodes early in the flights of Apollo 8 and 9, confirming Russian experiences in spacecraft more commodious than Mercury and Gemini, suggest that larger volumes, while necessary for longer missions, will also require an acclimatization period and possibly anti-vertigo interior design.

The limited volumes and provisions of spacecraft to date have also contributed to other problems, such as: extensive time and effort required in "housekeeping", food preparation, waste management, retrieval and stowage of both personal and experimental equipment; sleep distrubances caused by noises produced by another crew member who was awake; mobility obstruction by umbilicals, other crewmen, control panel projections, etc.

PRESENT MEDICAL POSITION

Amount of Spacecraft Volume

The principal factors which influence volume requirements are (1) number of crewmen, (2) types of activities to be performed, and (3) mission duration. For durations of 60 days and above, 150 cubic feet/man is probably an absolute tolerance threshold, and 600-800 cubic feet/man represents the adequacy threshold range. An optimal volume for a multi-man crew is not necessarily a linear multiple of the requirements of an individual crewman.

Utilization of Volume

Available volume should be divided and utilized according to functional requirements:

Functional Unit	Approximate Percentage Of Total Volume
Work unit: Command station, experimentation area, maintenance and repair workshop.	40%
Public unit: Wardroom for food preparation, dining, communal recreation, leisure and exercise.	25%
Personal unit: Individual quarters for sleeping, private relaxation and recreation, personal storage. A plastic tent or other enclosure can convert an individual's quarters into an isolated sick bay.	20%
Service unit: Personal hygiene-waste management station, laundry, public storage, sick bay.	15%

For missions outside of the magnetosphere, a radiation "storm cellar" must be incorporated into the design.

While it is desirable to separate physically these units and to provide each individual an area all his own, the use of permanent partitions must be weighed against access, mobility, and safety considerations. The broad design goals are to maximize "roominess" and to minimize clutter and obstructions to traffic flow within the spacecraft. The length of a movement path should be inversely related to its necessary frequency to usage. To achieve these goals, it may be necessary to employ flexible partitioning and multiple usage of areas.

Restraint Systems and Mobility Aids

A zero-g spacecraft must have a system of permanent restraints in high work-density areas and key-traffic nodes, and these restraints must be tailored to the specific activities performed in a certain area (e.g., food preparation, body hygiene, etc.). In addition, a universal system of portable, easily-attachable restraints which can be used in a variety of situations and tasks is necessary. Both hands should be free for use in work restraint arrangements. Three-point restraints (e.g., "window-washer's belt" plus foothold) or two-point rigidizable restraints should be used. Provision must be made for one-hand operation of any device in an area where the other hand may be needed for restraint.

Mobility aids are complementary to restraint systems. These aids must incorporate provisions for preventing or damping tumbling and rolling. Low impact stops must also be insured.

Padding is required for surfaces where bumps are likely. Grips, handles, and attachment points must also be designed to prevent clothing snagging and contact injuries.

Fittings and Furniture

Furniture design must conform to the special requirements of zero-g: Restraint must be adequate but also permit movement and readjustments within a workspace; small equipment and tools used while "on" a piece of furniture must be restrained as well as the astronaut; the need for padding of furniture is reduced by lack of gravity press. Portable furniture must be easily handled in weightless transport. Elimination of hazardous features such as sharp or pointed corners is, of course, mandatory. Consistency of directional orientation within a given work area must be maintained.

Storage, both temporary and long-term, is a major problem in zero-g. Velcro attachment points, pouches, and cannisters must be both abundant and well-organized. Provisions must be made for the expansion of bulk from pre-packaged minimum sizes.

Illumination, Decor and Color

Lighting is an important environmental factor for both operational efficiency and mood effects. Lighting plans and patterns should be carefully organized and protected from disruption by other service elements. Lighting should be organized to emphasize "spaciousness". Fixture design must eliminate safety hazards. Since there is no fixed eye-level in zero-g, glare conditions are even more important than on Earth. Indirect, diffuse, non-glaring illumination with a supplementary directional system is called for. Generally, light fixtures should have a surface brightness of less than 2 candles per inch. A 30% drop-off factor with fluorescent lamps should be incorporated, (see Table 2).

Color and decor can help to organize an environment, maintain spatial orientation, provide directional cues for safety purposes, make narrow spaces appear to be wider, and create a sense of restfulness or stimulation. For an excellent example of the use of colors to enhance a spacecraft environment, see Reference 5.

Ambient Noise Levels

Continuous Exposure Limits:

Noise of octave or wider band: 85 db max.

Noise of 1/3 octave or narrower band: 75 db max.

Institute ear protection at 10 db below these levels.

Peak Exposure Limits: (not more than 3 min/day)

Noise of octave or wider band: 120 db max.

Noise of 1/3 octave or narrower band: 115 db max.

Speech Interference Level: less than 55 db

S.I.L. = Mean of db levels within 3 octave bands between 600 and 4800 cps.

FUTURE EFFORTS

The vast bulk of experimentation and testing of habitability parameters must be done on Earth. For a meaningful experiment one should have the capability of varying independent variables to at least a limited extent. The amount of such variation possible in space is severely constrained. The dependent variables (human responses) are statistical in nature, so that repeated trials will be required. The primary functions of orbital activity should thus be (a) to determine if the vehicle design and implementations are adequate, and (b) to uncover considerations and factors that were not apparent in ground testing and analysis. Appropriate techniques for carrying out these determinations in orbit include: Crew comment questionnaires and logs, time-and-motion recordings of crew activities and medical-behavioral monitoring. The end product should be a set of transfer functions, so that results of ground-based testing can be confidently translated into spacecraft design criteria.

Amount of Volume

Experimentation is probably best directed towards exploring utilization of volume, spacecraft architecture, etc., rather than volume *per se*. But a minimum design value must be maintained.

Utilization of Volume

Ground-based Research: Detailed analysis and mock-up experimentation on work-space necessary for specific operational tasks. Include zero-g simulation.

Explore alternative configuration with aim of minimizing feelings of "confinement". Particularly, develop flexible partitioning and common usage.

In-flight Research: Perform specific tasks to validate work-space figures derived in zero-g simulation. Determine transfer function from simulation to flight.

Provide astronauts in flight with capability of altering partitioning. Record preferred configurations and amount of variation.

Decor-color

Ground-based Research: Initiate industrial design studies of use of color-decor to minimize "confinement". Explore use of visual display panels to permit variety.

Furniture, Mobility-restraint Aids

Ground-Based Research: Extensive zero-g simulation work to determine design principles for furniture, mobility and restraint aids.

In-flight Research: (includes Decor-Color) Validate ground derived principles by means of: Crew comment - logs, questionnaires, tape recordings; time-and-motion studies - photographic record; specific tasks and maneuvers - record time to performance, errors, etc.

Illumination

Ground-based Research: Explore omni-directional lighting schemes which permit full utilization of zero-g advantages. Use zero-g simulation techniques.

In-flight Research: Validate ground based studies. Mission might be equipped with rheostat controls and flexible lighting to collect data on preferred intensity levels and patterns.

Ambient Noise Levels

Ground-based Research: Conduct tests of operational system to identify noise levels. Design and develop protective aids. Determine effect of noise on communication.

In-flight Research: Conduct tests of operational system to identify noise levels. Periodic (monthly) hearing tests if noise levels near thresholds.

References

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5. Raymond Loewy, William Snaith, Inc. Habitability Study. AAP Program. Feb., 1968.

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TABLE I

CONFINEMENT STUDIES ON HUMANS

MARKED IMPAIRMENT WAS CONSIDERED TO BE MANIFEST PSYCHOPHYSIOLOGICAL CHANGE WHICH MIGHT PREJUDICE THE SAFETY OR SUCCESSFUL OUTCOME OF A MISSION. DETECTABLE IMPAIRMENT WAS CONSIDERED TO BE PRESENT IN A SITUATION WHICH WAS TOLERABLE, BUT WAS ACCOMPANIED BY MEASURABLE EVIDENCE OF DISTURBANCE WHICH COULD REDUCE PROFICIENCY. THE CLASSIFICATION OF NO IMPAIRMENT INCLUDED THOSE SITUATIONS WHERE SOME DISTURBANCE OF HOMEOSTASIS OR COMFORT MIGHT HAVE EXISTED WITHOUT LOSS OF PROFICIENCY.

Type of Study	Operational Conditions	Volume per man (cu. ft.)	Duration (days)	Impairment * Psych	Impairment * Physio	References
Simulator Single	SAM one-man	47	7	3	2	AF-SAM-59-101, 1959
	SAM one-man	47	1½	2	1	AF-SAM-60-80, 1960
	Vostok one-man	90	?1	1	1	FTD-TT-62-1619, 1962
Simulator Multi	Lockheed-Georgia OPN 360	183-250	15	2	2	WADD-TR-60-248, 1960
	HOPE II	187	15	2	2	WADD-AMRL-TDR-63-87, 1963
	HOPE III	110	30	2	2	WADD-AMRL-TDR-63-87, 1963
	HOPE IV & V	110	12	2	2	WADD-AMRL-TDR-64-63, 1964
	HOPE VI & VII	187	12	2	2	WADD-AMRL-TDR-64-63, 1964
	Navy ACEL	75	7	2	2	NAMC-ACEL-383, 1958
	Navy ACEL	75	8	2	2	NAMC-ACEL-413, 1959
	N. A. A. conical	67	7	2	2	IAS Meeting, Los Angeles, 1962
	N. A. A. cylindrical	375	7	1	1	AIAA and ASMA Conf., L. A., 1963
	N. A. A. disc	800	4	1	1	AIAA and ASMA Conf., L. A., 1963
	SAM two-man	106	14	2	2	<u>Aerospace Med</u>., <u>30</u>:722, 1959
	SAM two-man	106	17	2	2	<u>Aerospace Med</u>., <u>32</u>:603, 1961
	SAM two-man	106	30	2	2	SAM-TDR-63-27, 1963
	Republic	211	14	1	1	RAC-393-1, 1962
	Douglas	250	30	1	1	ASME Conf., Los Angeles, 1965
	GE	215	30	1	1	GE Doc. 64-SD-679, 1964
	Martin Baltimore	133	3	1	1	MAR-ER-12693, 1962
	Martin Baltimore	133	7	1	1	IAS-63-18, 1963
	NASA Ames	61.5	7	2	2	NASA-TN-D-2065, 1964
	WADC long range	140	5	2	2	<u>Aerospace Med</u>., <u>30</u>:599, 1959
Confined Chamber	U. of Maryland (Single)	1368	152	3	3	Univ. of Maryland, 1963
	U. of Georgia (Multi)	65	3	2	2	GEOU 226-FR, 1963
	U. of Georgia "	52	3	3	2	GEOU 226-FR, 1963
	U. of Georgia "	52	4	3	2	GEOU 226-FR, 1963
	U. of Georgia "	52	14	3	2	GEOU 226-FR, 1963
	U. of Georgia "	39	7	3	2	GEOU 226-FR, 1963
	USNRDL "	117	14	2	2	USNRDL-TR-418, 1960
	USNRDL "	117	5	2	2	USNRDL-TR-502, 1961
	Lockheed-Georgia (Multi)	125	4	1	1	WADD-TR-60-248, 1960
	"Coffin" (Single)	28	7	3	3	<u>Science</u>, <u>140</u>:306, 1963
Cockpit	F-84	<30	2 1/3	2	2	WADD-TR-55-395, 1955
	WADD capsule	27.5	2	2	1	WADD-ASD-TR-61-577, 1961
Vehicle	APC M59	30	1/6	1	1	AHEL-TM-3-60, 1960
	APC M113	23.3	1/3	2	2	AHEL-TM-17-60, 1960
	APC M113	28	1/2	2	2	AHEL-TM-1-61, 1961
	APC M113	25.5	1	3	?	AHEL-TM-23-61, 1961
	APC M113	25.5	1	3	3	AHEL-TM-7-62, 1962
Submarine	Nautilus	1600	11	1	1	USN Med. Res. Lab. Rept. 281, 1957
	Seawolf	570	60	1	1	USN Med. Res. Lab Rept. 358, 1961
	Nautilus	570	4	1	1	<u>USAF Med. J.</u>, <u>10</u>:451, 1959
	Triton	570	83	1	1	"Unusual Environments and "Human Behavior" 1963
Chair	SAM	< 25	4	1	3	<u>Aerospace Med</u>., <u>35</u>: 646, 1964
Bed	Lankenau	< 25	45	1	3	WADD-AMRL-TDR-63-37, 1963
	SAM	< 25	28	1	3	<u>Aerospace Med</u>., <u>12</u>:1194, 1964
	SAM	< 25	14	1	3	<u>Aerospace Med</u>., <u>35</u>:931, 1964
Spacecraft	MA-6	47	1/3	1	1	NASA Doc 398, 1962
	MA-7, 8	47	1/2	1	2	NASA SP-6, 1962
	MA-9	47	1 1/2	1	2	NASA SP-45, 1963
	Vostok I	90	1/2	1	1	FTD-TT-62-1619, 1962
	Vostok II	90	>1	1	2	FTD-TT-62-1619, 1962
	Gemini III	40	1/5	1	1	
	Gemini IV	40	4	1	2	Gemini Mid-Program Conf. Proceedings, Part 1 & 2 MSC, Houston, Texas, 1966
	Gemini V	40	8	1	2	
	Gemini VI	40	1	1	1	
	Gemini VII	40	14	1	2	

*NO IMPAIRMENT (GRADE 1), DETECTABLE IMPAIRMENT (GRADE 2), AND MARKED IMPAIRMENT (GRADE 3).

TABLE 2

	General Level & Quality	Supplementary Spots (Flexible)	Max. Contrast Ratio	Suggested Colors
Work Areas:	20-50 ft. candles	To 100 ft. candles	3 to 1	Cool, Unsaturated with bright, contrasty accents & trim.
Personal & Recreation Areas:	5-10 ft. candles Incand. or modified fluorescent	To 30 ft. candles	5 to 1 Contrast desirable.	Warm, saturated "homey"
Service Areas:	10-20 ft. candles Incand. or modified fluorescent		3 to 1	Light; tints, unsaturated.
Emerg. System	2-5 ft. candles			

Workplace Reflectances: Console panel: 20-40%; instruments: 80-100%; "floors," walls, "ceilings:" 40-60%.

CREW SELECTION, SIZE, AND COMPOSITION

STATEMENT OF THE PROBLEM

As crew size and mission duration increase, the implications of optimum medical and physiological selection criteria also take on added importance. An ideal selection program would enable management to obtain a crew each of whose members would successfully complete any required training and would perform throughout the mission duration at a high level of efficiency. The state-of-the-art falls far short of this ideal objective but certain principles have been established largely through empirical observations on group performance in isolated working environments such as polar expeditions, submarine crews, mountain climbing expeditions, etc. Paying due attention to these principles should enhance the probability of mission success while total disregard for them would almost surely result in serious mission degradation or failure due to human inadequacies within the crew. Selection must be made not only on the basis of individual qualification of crew members, but also with a view toward the ability of each crew member to work effectively and harmoniously with the entire crew.

The number of people who should comprise the crew depends more upon task analysis than on medical considerations. However, social psychological factors should be considered. The various factors influencing choice of crew size are outlined in the Appendix.

PAST MEDICAL APPROACH

The criteria used in the selection of the current astronauts are defined in the Candidate Evaluation Program (Ref. 1). For the first seven astronauts, the pool of potential candidates were qualified jet pilots with more than 1,500 hours of flying time, graduates of test-pilot school, in excellent physical condition, under 40 years of age, and less than 5 feet 11 inches in height. The ways in which these basic criteria changed for later groups of astronauts, who were selected more for technical and scientific skills than flying experience, are indicated in Tables 1 and 2. All candidates were subjected to comprehensive physical, physiological, biochemical, medical, and psychological examinations.

The psychological properties sought in potential astronauts included:

a) high intelligence, particularly with mathematical and spatial aptitude;
b) able to contribute to development of space hardware and program planning;
c) an ability to work closely with others;
d) able to tolerate extreme isolation without anxiety;
e) reliable and consistent;
f) sufficient adaptibility and flexibility to cope with emergencies;
g) deliberate rather than impulsive;
h) exceptional stress tolerance;
i) motivated by mission-oriented rather than personal-achievement goals.

The psychological screening included psychiatric interviews, many psychological tests, and observation under stressful test conditions.

The importance of psychological factors in the final selection process is emphasized in the Evaluation Program report:

1. Psychological stability is the most important consideration in evaluating a candidate. The intelligence, maturity, and motivation of a candidate are vital areas to be assessed before rendering a recommendation.
2. Excellent physiological performance was a secondary consideration in the final Committee recommendations.
3. The main value of a severely stressful physiological test was the interpretation of the psychological response to that stress test. Whenever a subject terminated a severe test for psychological reasons, he was not recommended by the Committee (Ref. 1, p. 99).

The overall validity of these selection procedures, in conjunction with the further selection of specific flight crews during training procedures, is attested to by the inflight performance of the astronauts to date.

PRESENT MEDICAL POSITION

The medical criteria which have been established for selection of military aviators are generally appropriate for selection of space station crew members. Requirement for visual acuity and certain other pilot-related physical characteristics such as rapid reaction time and eye-hand coordination skill would be relaxed for scientist and technician crew members who are not required to control or maneuver the spacecraft. Adaptation of existing military and civil aviation medical standards rather than development of new physical criteria for selection of space station crew members should prove sufficient for the establishment of medical selection criteria. Applied research and development is indicated, however, in the area of psychological aptitude for space flight among scientists and technicians who have not already been preselected through the process of becoming professional pilots.

While gross personality characteristics which would render candidate crew members unsuited for space station assignment can be identified using currently available techniques, the best test of crew compatibility is to assemble a full candidate crew and observe the crew members during a prolonged period of living and working together under conditions as nearly representative of the actual mission situation as is practicable. Under conditions of enforced continuous close association, subtle individual characteristics become major factors in successful interpersonal relationships and concealed idiosyncrasies emerge which degrade and in some instances have destroyed the functional integrity of the entire crew. It is considered mandatory that careful attention be paid to timing and structuring the training program to allow for the demonstration of crew compatibility and to permit the replacement of individual crew members who do not fit into the group successfully as time goes by. Motivation, discipline, command structure, training, and individual intelligence of the crew are all important factors. Demonstrated crew compatibility ranks along with all of these in contributing toward mission success.

Thus, the following major new elements in the selection program are necessary:

1. Attention to appropriate standards and criteria for interpersonal capabilities during astronaut selection;
2. Systematic observations and evaluation of crew interaction characteristics during training; and
3. Systematic on-board observations and postflight debriefings.

Crew Size and Composition

Minimum Crew Size	Number
1. Mission Commander[1] (Pilot)	1
2. Flight Surgeon[2]	1 or 0
3. Physical Scientists[3]	1 or 2
4. Engineer[4] (Back-up Pilot)	1
Total[5]	4

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(1) Mission Commander: responsible for mission management (planning) and participates in research and maintenance work load.

(2) Flight Surgeon: responsible for physiological surveillance, sanitary supervision and crew health. He also carries out bioscience research.

(3) Participate in maintenance work load and carry out research in the physical sciences area.

(4) Engineer: responsible for maintenance work. He also participates in research activities.

(5) If around the clock control station monitoring is required, then the minimum size increases to 6 instead of 4 crewmembers.

The presence of a physician as a biomedical scientist on the crew is recommended. This man would have primary responsibility for the proper conduct of the in-flight biomedical research program and should materially enhance the overall probability of mission success by furnishing in-flight medical support to the crew. A physician backed up by systems designed in accordance with optimum human engineering and preventive medicine practices and appropriate medical support of the crew through their preflight training period should be able to manage all of the medical problems which would arise in the course of a three-month to one-year mission with relatively simple on-board equipment and treatment capability. This capability should include facilities and supplies adequate for the diagnosis and treatment of infectious diseases, simple fractures, minor surgical emergencies, and the initial care and stabilization of severely injured crewmen to prepare them for evacuation to ground-based medical facilities.

FUTURE EFFORTS

a. Identify mission requirements with respect to crew's operational requirements:

   (1) Command/Control Operations.

   (2) Experiment Operations.

   (3) Personal Requirements (sleep, hygiene, housekeeping, etc.).

b. Conduct systematic observations during training to determine crew compatibility and functional proficiency (as a group).

c. Develop methodology and criteria for observations in b above.

d. Review criteria for interpersonal interaction capability in small groups for long-duration with respect to initial astronaut selection program.

e. Develop methodology and criteria for systematic observations on-board during space flight mission with respect to crew interaction and functional proficiency (as a group).

f. Develop timeline assessment methodology to assure:

   (1) Appropriate crew composition.

   (2) Appropriate mission planning and mission timeline allocation.

REFERENCES

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GROUP	NUMBER SELECTED	DATE OF SELECTION	BASIC REQUIREMENTS			
			GRADUATE OF TEST PILOT SCHOOL	JET PILOT RATING	FLYING TIME	EDUCATION
1	7	Apr 59	REQ	REQ	1500 Hrs	BS in Eng or Equivalent
2	9	Sep 62	REQ	REQ	1500 Hrs	BS in Phys, Biological or Eng Sciences
3	14	Oct 63	OPT	REQ	1000 Hrs	Same as for GP 2
4	6	Jun 65	OPT	OPT	OPT	Graduate work in the Phys, Biological or Eng Sciences
5	19	Apr 66	OPT	REQ	1000 Hrs OPT	Same as for GP 2
6	11	Aug 67	OPT	OPT	OPT	Same as for GP 4

Table 1 : ASTRONAUT SELECTION CRITERIA

Table 2

COMPARISON OF ASTRONAUT GROUPS

AT TIME OF SELECTION

	1959	1962	1963	1965	1966	1967
AGE	34.5	32.5	30.0	31.2	32.8	33.0
COLLEGE YEARS	4.3	4.6	5.6	8.0	5.8	8.3
FLIGHT HOURS	3500	2800	2315	•	2714	•

•PILOT EXPERIENCE NOT REQUIRED FOR SELECTION OF SCIENTIST ASTRONAUTS

APPENDIX

CREW SIZE

FACTORS AFFECTING CREW SIZE

Demanding a Size Increase

1. Interpersonal considerations (up to a point)
2. Work load requirements (including training)
3. Statistical validation of medical results.

Demanding a Size Decrease

1. Weight penalties
2. Volume per man requirements
3. Crew rescue capability
4. Logistics and resupply considerations.

INTERPERSONAL CONSIDERATIONS

Crew Size of One

No social interaction. Isolation, as a psycho-physiological stress, will most certainly be experienced.

Crew Size of Two

Limited social interaction combined with inter-personal overexposure could be expected to result in irrita-bility and friction.

Crew Size of Three

Problem with 2 vs. 1 splits. Minority is isolated individual, but majority is not large enough to dominate com-pletely. Also limited social interactions.

Crew Size of Four

Good provided authoritarian structure is maintained. Otherwise, 2 vs. 2 deadlocks can develop. 3 vs. 1 exerts tremendous pressure on deviant.

Crew Size of Five (or greater)

Acceptable. However, as crew size increases beyond 8-10, management, communication, role structure problems assume great importance. Additionally, there is a diminution in the sense of belonging to and identification with the group as a whole. Clique formation increases.

WORK LOAD REQUIREMENTS (See Table I)

Crew Functions (Collective Effort)

1. Flight operations (maneuvering, transfering, docking, EVA)
2. Mission management (advance planning and opportunistic activities)
3. Spacecraft subsystems performance monitoring (continuous?)
4. Preventive and corrective system and subsystem maintenance
5. Medical surveillance and sanitary supervision
6. Scientific research (astronomy, zero-g physics, materials technology, biomedicine, biosciences, remote Earth sensing, etc.).

Personal Activities

1. Recreation
2. Maintenance of physical fitness
3. Scientific training (skill retention)
4. Spacecraft systems training and cross-training (pre-mission).

Scheduling

1. Work-rest cycles
2. Minimum duration of sleep
3. Maintenance of diurnal rhythms.

WEIGHT PENALTIES

Earth Entry Module ($\sim$ 3700 lb/man)

Mission Module ($\sim$7000 lb/man)

VOLUME PER MAN REQUIREMENTS

Free Volume ($\sim$ 600 ft^3/man)

Utilization of Free Volume

1. Personal unit
2. Public unit (socializing, recreation, gym)
3. Service units (waste management, kitchen, stowage, sanitation)
4. Work units (lab areas and mission control station)
5. Clinical unit.

CREW RESCUE CAPABILITIES

Four to six astronauts under any given time in case of emergency using uprated Apollo hardware.

LOGISTICS AND RESUPPLY CONSIDERATIONS

Consumables ($\sim$ 10 lbs/man per day)

Expendables ($\sim$ 5 lbs/man per day)(Size Dependent)

Expendables ($\sim$ 15 lbs/day)(Size Independent)

Present CSM Survival Times $\sim$ 56 Days

If the station is designed as a large complex community, the logistics of resupply become the limiting constraint and medical evacuation of the sick and injured personnel along with medical resupply logistics must be considered.

TABLE I

AVERAGE CREW WORKLOAD AS A FUNCTION OF CREW SIZE

THE DATA PRESENTED BELOW WAS USED AS A BASIS FOR THE CREW SIZE COMPARISON. THOUGH IT WAS FELT CREW SIZES OF THREE-FOUR COULD MANAGE THE STATION AND COMPLETE MOST OF THE BIOMEDICAL/BEHAVIORAL PROGRAM, THE CAPABILITY OF THE LARGER CREW SIZE (SIX - NINE) TO ACCOMMODATE THE EARTH RESOURCES, ENGINEERING, AND SCIENTIFIC EXPERIMENTATION IS SIGNIFICANT.

DAILY CREW WORKLOAD SUMMARY

ACTIVITY	MAN-HOURS PER DAY			
	PER MAN	3 MEN	6 MEN	9 MEN
PERSONAL MAINTENANCE (INCLUDES SLEEP, EATING, REST HYGIENE)	12.3	36.9	73.8	110.7
CONTINGENCY (10%)	2.4	7.2	14.4	21.6
STATION KEEPING TASKS	VARIABLE	15.0	15.0	15.0
TOTAL HOURS LEFT FOR EXPERIMEN TATION (INCLUDES BIOMEDICAL/BEHAV-IORAL EXPERIMENTS)	VARIABLE	12.9	40.8	68.7

WORK, REST, SLEEP AND RECREATION

STATEMENT OF THE PROBLEM

Given the cost of each man/hour in space and the impact of each crewman's activity on the overall success of a mission, it is essential to maintain a high level of astronaut performance throughout the duration of a spaceflight. For extended-duration missions, as in long-distance races, the problem is one of pacing. The scheduling of crew activities must not merely avoid gross overload, it must be structured to combat gradual degradations in interest and capacity. Contingency scheduling, such as for major system repairs or high-density scientific observations, must be as carefully planned as nominal schedules, and the crew must have the energy reserves to cope with such contingencies.

The content of crew activities is also more critical on long-duration missions than on relatively short flights. Each astronaut's workload should be sufficiently meaningful and varied to maintain personal involvement and satisfaction. What work is "meaningful" for an individual is dependent, of course, on his personality and past experience, so duty planning must interact extensively with crew selection and training procedures. Also, developments in the reliability, ease of maintenance, and automated operation of spacecraft systems heavily influence the options avialable for work assignments, the skill, composition of the crew, the need for cross-training, etc.

As is detailed below, sleep problems have been a recurrent phenomenon in spaceflights to date. Many of the causes of these sleep difficulties will presumably be eliminated in long-duration space systems, particularly since the extended time period will permit greater adaptation to sleep in space. Nevertheless, because emergency conditions may require prolonged wakefulness, sleep deprivation effects must be considered in mission planning. Sleep factors also affect system design in the question of watch scheduling, i.e., whether it is necessary to have one or more crewman awake at all times.

Provisions for and time allotted to exercise and recreation are also necessary for maintaining the morale and efficiency of long-term mission crews, for physiological as well as psychological reasons. The recreation possibilities must suit the personal preferences of the crewmen and, additionally should serve to:

a) Counter the detrimental physiological effects of weightlessness;

b) Combat feelings of confinement and monotony;

c) Serve as a substitute for social interactions and sources of stimulation left behind;

d) Promote or reinstate group cooperation and cohesiveness.

PAST MEDICAL APPROACH

Work Schedules

In U. S. spaceflights to date, the task demands of mission timelines, although fulfilled remarkably well by the various crews, have often been in excess of levels desirable for long-term spaceflight. Many mundane tasks, such as equipment stowage and housekeeping, have proven more difficult and time consuming than anticipated, due to weightlessness, limited space, and interaction with other mission responsibilities. The Gemini flights demonstrated that extravehicular activity is especially demanding.

> "Chronic fatigue and degraded physical condition may have been a problem during extravehicular activity. Sleep during the first night of each flight was inadequate, and preparation activities for extravehicular maneuvers were detailed and fatiguing. Furthermore, the pace of preflight activities and the pressures of planning, training, and preparation to meet a flight schedule predisposed the crew to fatigue. During the final weeks of preparation for a flight, each crew found that time for rest, relaxation, and even physical conditioning was at a premium, and often these activities were omitted... The major factors which appear to have produced the highest workload during the extravehicular activity are high suit forces, insufficient body aids, and thermal stress. The success of Gemini XII conclusively demonstrated that these factors can be minimized through careful planning."
>
> (Reference 1, pp. 113, 117)

Fatiguing flight plan requirements have been cause for crew comment and some data loss on Apollo flights 7-9.

Sleep Problems

Sleep difficulties have been present on most U. S. and Russian spaceflights of sufficient duration to require sleep (see Ref. 2, pp. 16-83 - 16-85). These problems have taken the form of:

1) Difficulty falling asleep during certain scheduled sleep periods of the mission, e.g. "The crews have never slept well on the first night in space" (Ref. 1, p. 214).

2) Restlessness, frequent awakening, and abnormal depth - time course of sleep. E.g., "The command pilot (on GT-7)... did become increasingly fatigued over a period of several days, then would sleep soundly and start his cycle of light, intermittent sleep to the point of fatigue all over again." (Ref. 3, p. 241; see also EEG data in Refs. 3, pp.423-429; 4).

3) Fatigue due to the above and mission demands.

Secoborbital was prescribed to offset factors non-conducive to restful sleep in Apollo 8 and 9, and dextro-amphetamine sulfate was taken on several occasions by fatigued Mercury and Gemini crewmen prior to reentry.

The probable causes of these sleep difficulties include:

1) The unfamiliar environment for sleep: weightlessness, sitting upright, cramped quarters, restraints, etc.
2) Arousal effects of potential dangers, feelings of responsibility, frequent orienting behavior to insure that all systems are functioning properly.
3) Task demands of the mission, requirements of house-keeping and observing, communications contacts.
4) Positive excitement inherent in mission, "fascination of the crew with the unique opportunity to view the Universe, "(Ref. 1, p. 216).
5) Sleep-wakefulness schedules that did not coincide with the astronauts' usual ground routines.

6) Disturbances (e.g. firing of thrusters, removing items attached with Velcro) caused by non-simultaneous sleeping of crew.

Recreation - Exercise

Recreation on spaceflights to date has been largely limited to exercise with in-flight exercise devices and occasional social conversations with ground control personnel. The amount of in-flight exercise has varied from flight to flight. On the shorter Gemini flights, with their intensive rendezvous and EVA schedules, no specific conditioning exercises were employed. On the 14-day Gemini 7 mission, three 10-minute exercise periods were planned and carried out each day.

PRESENT MEDICAL POSITION

Work Nature and Load

An astronaut's assigned work should be meaningful, varied, and in accord with his educational specialty, personality predilections, and training experience. The necessity for extended periods of vigilant monitoring should be minimized by assigning such functions, as much as systems engineering will permit, to mission control or the on-board computer. Scientific instruments should provide on-line display capability to sustain astronaut's interest and allow him to identify unusual phenomena.

Normal workload should be at the metabolic rate equivalent to approximately 2 lbs. of oxygen consumption per man per day. Transient workloads should not exceed 0.47 lbs. of O_2/man/hour. Sustained workload should not exceed 3.5 lbs. of O_2/man/day.

Work-rest Scheduling

Although other types of schedules appear to be viable (see Ref. 2), the safest course is to aim for conventional, Earth-based type schedules unless the particular type of mission or experiment requirement strongly demands alternate scheduling. This means planning for 12 hours of work, four hours of leisure, and eight continuous hours for sleep during each 24-hour cycle. Continuous work periods without a break should not exceed four hours in length. Simultaneous sleeping of whole or majority of crew is also desirable. The timing of the sleep period should coincide with the crew's Earth-based diurnal cycle or, if not, the crew should acclimatize to the new schedule for at least a week before the start of the mission. Contingency schedules should allow at least four consecutive hours for sleep. A periodic day allotted for "rest, relaxation, and review" is also desirable.

Sleep Deprivation

Earth-based research (Ref. 5, 6) has shown that the primary effects of sleep deprivation are:

1) Lapses, short periods when performance stops or falters;
2) Loss of speed in self-paced tasks;
3) Loss of accuracy in work-paced tasks.

Task aspects which tend to increase such impairment include:

a) Longer task duration;
b) Greater signal and response uncertainty;
c) Less knowledge of results, interest, and incentive;
d) Greater monotony.

Non-task factors which tend to reduce impairment include:

e) Noise or other arousing environmental stimulation;

f) Physical exercise preceding task performance;

g) Moderate doses of D-amphetamine and similar stimulants.

Sleep deprivation effects increase with time awake, but not monotonically. Performance effects wax and wane, with a greater impact at "night" than during what would be the subject's "day." Furthermore, there are substantial individual differences in the effects of sleep deprivation on performance.

On the basis of these principles, the following recommendations can be made regarding sleep hygiene during both normal and emergency conditions on future space missions:

1) Nominal and contingency timelines should be flexible, with feedback of the crew's alertness - fatigue status before non-time-locked task scheduling. This includes allowing for likely times in a space mission when the natural excitement of the situation (e.g., first night in space, arrival at a celestial body) may prevent sleep.

2) During unavoidable sleep deprivation periods, as many tasks as possible should be transferred to ground or automatic control.

3) Crews should be selected for their ability to sleep soundly in the face of stress and excitement, and to be resistant to the effects of sleep deprivation. These two qualities seem to be correlated (Ref. 7).

4) Crews should be trained to anticipate and compensate for the effects of sleep deprivation. For example, automatically performing a familiar task when fatigued, instead of pacing oneself through lapses, can lead to more errors of commission.

5) When necessary, careful drug assistance should be used to induce sleep and compensate for sleep deprivation. Drug use in space, however, is not without risk. The effect of a drug may be altered by weightlessness, radiation, and the multiple other stressors associated with spaceflight. Furthermore, drug-induced sleep is not physiological sleep, and selective deprivation of certain sleep stages (a frequent drug effect) can cause irritability and distortion of judgement. Excessive use of amphetamines can have similar judgment-impairing effects, as well as cardiovascular side-effects.

Recreation - Exercise

A definite exercise regimen (with appropriate space provided) will be required on long-duration spaceflights to counter the effects of weightlessness on physiological functioning, as well as for the usual physical and psychological benefits of exercise. Other recreational facilities should combat confinement, enhance sensory variation, reduce social friction, and should be of sufficient variety to permit shifts in interest after extended time periods. These facilities should include book- and film-type provisions, with individual preferences incorporated. Communication facilities should have capability for social communications between crew and family and friends on Earth.

FUTURE EFFORTS

Work Nature and Load

Define optimum meaningfulness, feed-back, complexity, and variety necessary for sustained performance. Define workload which permits maximum sustained output with emergency reserve capacity. Develop cross-training and skill maintenance techniques.

Work-rest Scheduling

Develop contingency schedules and flexible timeline procedures which incorporate on-line data on crew performance status. Define systematic observation methodology to assess crew proficiency in flight with a given work-rest schedule. Continue ground-based study of effects of unusual work-rest schedules.

Sleep Factors

Explore effects of component spaceflight factors on quality and quantity of sleep. Continue development of in-flight sleep monitoring devices and procedures. Study performance upon awakening from sleep to help determine need for around-the-clock watch. Develop training techniques for resistance to sleep deprivation and voluntary control of relaxation-sleep onset. Incorporate sleep capabilities into crew selection criteria.

Recreation - Exercise

Use data from in-flight experiments (Metabolic Cost, Whole Body Exercise, etc.) and ground-based studies to specify necessary exercise regimen. Institute preflight conditioning with exercises to be utilized in spaceflight.

Study effects of different forms of recreation on group cohesion, confinement feelings. Survey recreation preferences of crew members. Develop necessary recreational hardware and social communication links.

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OCULO-VISUAL EFFECTS

STATEMENT OF THE PROBLEM

The importance of clear, binocular vision to spaceflight crew personnel cannot be overemphasized. This sensory function supplies the major informational input to the astronaut. It necessarily follows that only spacecrew personnel with well functioning visual apparatus should be selected for duty on extended space missions. Routine ocular examination and classical philosophy on aircrew fitness then will not suffice for selection of crews for extended space missions. Astronauts assigned to such missions must possess clear, simultaneous, binocular vision. The flight tasks will require long concentration at the near point. Comfortable binocular vision is necessary for optimum performance in such situations. This has been established through experience with bombardiers and navigators assigned to USAF Strategic Air Command crews. Their duties require near point concentration and use of complex optical devices similar to those used in spaceflight. Those individuals with binocular vision problems have difficulty performing adequately in such jobs. Refractive error is another important visual factor. Careful attention must be paid to the refractive errors of astronauts. In many individuals the refractive state of the eye can change significantly in a year. Crewmen with uncomplicated, stable refractive conditions must be selected for extended missions. Prodomal glaucoma and incipient cataract also must be considered as complicating ocular factors in extended space missions. The problem of oculo-visual effects of extended space missions separates into two major areas, (a) preselection of spacecrew personnel to insure optimum visual performance based on improved or advanced understanding of oculo-visual requirements, (b) monitoring visual performance to detect any subtle changes which may occur.

PAST MEDICAL APPROACH

This problem is as old as flight medicine. A broad body of knowledge and experience has been developed over the years and the visual criteria used for selection of aircraft flight crews appears to be adequate. Close inspection, however, of these criteria shows many areas for improvement in theory, methods, and instrumentation. In the past U.S. Air Force visual standards have been the principle criteria for selection of space flight crew personnel. The measuring techniques and instrumentation for these tests in most cases provide only gross indications of the status of the visual function under test. In addition, the test data are highly variable.

PRESENT MEDICAL POSITION

Extended spaceflight will impose severe stresses on all physio-perceptual functions as well as the oculo-visual apparatus. In order to qualify man for extended space missions, spacecrew personnel for the six month mission must be thoroughly baselined oculo-visually. This baselining will be accomplished through development of improved examining methods, techniques, and instrumentation. Emphasis will be placed on more sensitive instrumentation and if possible fewer more definitive oculo-visual tests. The same, or if necessary, modified, oculo-visual instruments will be employed to monitor the oculo-visual status of the spacecrew personnel during the mission. The present assessment of the problem indicates that the following tests are a minimum for use during the mission: (1) binocular stereo acuity, (2) central color fields, (3) contrast threshold, (4) visual acuity, (5) heterophorias, and (6) intraocular tension. These oculo-visual measurements would not be an experiment per se but would be periodic monitoring of the oculo-visual apparatus to detect changes however subtle.

FUTURE EFFORTS

The Office of Advanced Research and Technology (OART) is conducting a vision test development through NASA Ames. This effort apparently is directed toward the Apollo Applications Program (AAP) and involves two Contractors in parallel efforts. It is not known how applicable these tests will be to the oculo-visual problems of extended space missions.

The IMBLMS development of NASA, MSC also includes the development of vision tests for use during spaceflight. The current direction given the IMBLMS Contractors encourages the employment of the vision tests outlined in the section on, "Present Medical Position." In any event the future efforts of the IMBLMS contractor will include these tests.

The work at NASA, MSC in the Visual Optics Laboratory has included liaison between the OART Contractors and also with the IMBLMS Contractors. It is hoped this coordination will give proper direction to these efforts. In addition, the Visual Optics Laboratory plans to assist in performing the oculo-visual portion of the astronauts periodic physical examinations and will conduct any research and development for the required methods, techniques, and instrumentation not covered by the OART and IMBLMS efforts.

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EXTRAVEHICULAR ACTIVITY

STATEMENT OF THE PROBLEM:

As future space missions become more ambitious, the astronaut will be required to perform activities which will be essential to mission success. For example, currently envisioned earth orbital missions may involve erection of telescopes and antennas for use in studying astronomy, advanced communications, and earth sciences and resources. Eventually, more permanent manned orbital stations will be in use which must be maintained and resupplied. In the more distant future, manned planetary missions will be undertaken with tasks involving maintenance, repair, inspection, assembly, fueling, and other activities. The capability required to support these missions will depend, among other things, on the astronaut's ability to efficiently operate in an extravehicular (EV) environment. Man's operational capability to perform these EV activities is a key factor in preparing for these advanced missions and must be developed along with other important technology areas. The task of developing these capabilities requires a logical and well-organized approach.

The Gemini Program proved the capability of man to function in the free space environment external to the relative safety of the spacecraft cabin. Gemini also demonstrated that man can perform useful tasks while EVA, but that these tasks must be carefully evaluated, planned, performed within certain limits, and supported by the proper use of the proper equipment. During Gemini EVA several physiological problems developed. There were indications that excessive workload might be a limiting factor during EVA. A postflight evaluation of data from Gemini IX-A and XI indicated that an excessive thermal load may have been imposed on the extravehicular pilot, and high respiration rates encountered during Gemini XI indicated that a buildup in carbon dioxide level may have been a problem. Since there were no actual data on thermal conditions or carbon dioxide levels, no direct measure of these problem areas could be made. This Gemini experience underscored the need for a carefully planned program of study into the problems associated with EVA and the need for a well-defined program to develop EVA into an acceptable operational mode. Inherent in this is the requirement for more extensive instrumentation in order to better monitor the physiological well being of the crewmen and to follow the activity level during EVA.

PAST MEDICAL APPROACH:

Gemini extravehicular bioinstrumentation consisted of the electrocardiogram and the impedance pneumogram. These parameters have been monitored during a great many physiological and psychological tests and under widely varying conditions. The existing pool of information has established the fact that heart rate responds to psychological, physiological, and pathological conditions. There are considerable individual variations in these responses; however, since a quantitative indication of workload actually experienced in flight appeared to be of primary importance, the feasibility of using heart rate as a quantitative indication of workload was investigated. On Gemini IX-A, X, XI, and XII, preflight and postflight exercise tests using the bicycle ergometer were performed on the pilots. During these tests, the subject performed a measured amount of work in increasing increments, while heart rate, blood pressure, and respiration rate were monitored and periodic samples of expired gas were collected for analysis. These data were translated into oxygen utilization curves and BTU plots. Timed volumes for expired $\dot{V}_E$, for oxygen $\dot{V}_{O_2}$, and for carbon dioxide $\dot{V}_{CO_2}$ were corrected to standard temperature and pressure, dry (STPD). Using these plots and the heart rate data obtained during each flight, an approximate workload curve was plotted against the EVA time line. These derived data were considered inaccurate, because changes in heart rate caused by thermal or environmental problems could not be taken into consideration. The psychological effect of a new and different environment also could have increased the heart rates without a corresponding change in metabolic rate. However, any error introduced by these factors would have increased the observed heart rate for a given workload level and introduced a margin of safety. This fact tended to increase the usefulness of such a plot in preflight planning and in inflight monitoring of EVA. When data from previous flights, altitude chamber tests, one-g walk throughs, and underwater zero-g simulations were examined in this manner, a qualitative indication of work expended on various tasks could be derived. This was important in the assessment of the relative physiological cost of various tasks and in the determination of acceptable tasks and realistic time lines during simulations and preflight planning.

Periods of exercise were included in both of the standup EVA's during Gemini XII. These exercises consisted of moving the arms away from the neutral position of the pressurized space suit. Both arms were brought from the neutral position to the sides of the helmet once each second for 60 seconds. An attempt was made to correlate heart rate data during these inflight exercise periods with preflight exercise tests. When compared in this manner, no significant difference appeared in the response to exercise performed before and during flight. It must be remembered, however, that only qualitative conclusions can be drawn from these data. Valid quantitative conclusions must await the results of more precise inflight medical experimentation in which controlled conditions and additional data collection are feasible.

PRESENT MEDICAL POSITION:

Man has the capability of performing useful work in the space environment. There are no indications that this ability is significantly altered during EVA if he is provided with an adequate life support and thermoregulation system, a spacesuit with wide mobility and low metabolic cost (as exhibited by the new constant volume suits), and with well designed mobility aids, and worksite tools and restraints.

Medical experience gained as a result of Gemini EVA has provided information which will be valuable in preparing for future EVA missions. The electrocardiogram and the rate and depth of respiration were useful, but only partially effective in assessing total physiological performance during EVA. The major factors which produced the highest workloads during EVA were resolved for Gemini XII. The success of Gemini XII EVA demonstrated that when these factors were understood properly, the medical response to EVA was very close to predictions.

Without specific knowledge or monitoring of the thermal and environmental conditions, a complete analysis of the physiological aspects of EVA can not be accomplished. Specific measurements which are lacking include: the carbon dioxide concentration, the space suit inlet and outlet temperatures and dewpoints, and the body temperature. Ideally, the actual measurement of metabolic rate is highly desirable but is beyond the state-of-the-art.

In the Apollo program, the development of EVA as a useful operational tool will be continued and will include a systematic program for evaluating both major tasks and discreet subtasks in one-g and in zero-g or one-sixth-g. It is hoped that in this manner, mission techniques and hardware will be developed to meet a specific purpose.

Medical monitoring during the Apollo program will, in addition to voice contact, consist of ECG, heart rate, and respiration rate. When the PLSS is utilized during EVA, more extensive environmental monitoring instrumentation will be available. This will include measurement of liquid cooled garment (LCG) ΔT and possibly CO_2 concentration in the later missions. Although not the ultimate, this will provide additional data from which to better assess the work levels achieved by the crewmen as well as increased safety monitoring capability.

<u>FUTURE EFFORTS</u>:

Emphasis of future efforts will be in the following areas:

(a) Develop new and improved communications and bio-instrumentation systems to assure adequate monitoring of crew activities and physiological well being. Of utmost importance is the development of a metabolic rate measurement technique and hardware which will permit direct, quantitative evaluation of the crewmen's activity level during EVA. A complete, detailed discussion of this requirement is contained in the section of this report dealing with energy metabolism.

(b) Institute a program to provide for the timely evaluation and development of techniques, methods, and hardware required to provide the capabilities necessary to support performance of the expected EVA tasks. EVA tasks and subtasks will be assessed using one-g walkthroughs and zero-g and/or one-sixth-g simulations.

(c) Continue the development of life support systems for EVA with emphasis directed toward production of space suits capable of supporting a wide range of EV missions and incorporating the required mobility and protective measures essential to successful EVA and toward the production of compact environmental control systems incorporating high heat load capability, simplified recharge capability, high density storage of oxygen, and indefinite shelf life.

(d) Provide increased capability for the monitoring of life support system environmental and operational parameters. Medical assessment of the crewmen during EVA can be accomplished with much greater confidence if these environmental and operational factors are known.

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ARTIFICIAL GRAVITY

STATEMENT OF THE PROBLEM

In planning for long-duration space flight it is important to decide soon whether or not artificial gravity will be needed, and if needed whether it should be obtained by rotating the entire vehicle or by means of a centrifuge subsystem on a zero-g space station. We consider first some of the factors important in the trade-offs between zero-gravity and artificial gravity obtained by vehicle rotation.

Advantages of Artificial Gravity

1. Rotation of the space station will partially offset the problems of crew performance, cleanliness and comfort in zero-g which are discussed in detail in the section on integrated performance in weightlessness. Small objects (particles and liquids) will settle to the floor instead of being randomly dispersed on all surfaces of the spacecraft interior. This avoids the problem of foreign particles (which could be toxic or infectious) getting into the eyes and lungs. This debris comes from shaving, food, meal preparation, etc. Large objects will be attracted to the floor strongly enough to provide frictional forces against which a man can perform torqueing and lifting tasks.

This simplifies the maneuvering of objects as well as body locomotion in the space station, and thereby simplifies crew training for space station operations. Gravity-induced convection currents in liquids and gases are present in the artificial-g environment.

2. The physiological problems discussed in the weightlessness section above will be less severe in artificial gravity than in zero-gravity. It is believed that the problems of bone demineralization, muscular atrophy and alterations of cardiovascular and otolith reflexes which are predicted for long duration exposures to zero-g would not be serious in a constant artificial gravity field. For example, artificial gravity would provide a load against which the heart and vessel walls would have to counteract. The presence of artificial gravity would continue to provide stimulation to the otolith organs (the gravity and linear acceleration sensors), which might need the constant stimulation with which it evolved on earth in order to continue to contribute to posture control.

Disadvantages of Artificial Gravity

1. Centrifugally obtained artificial gravity is different from earth gravity because the effects of rotation (e.g., Coriolis forces) are much larger than on Earth. The astronaut experiences several unusual effects in a centrifugal field. An object which becomes dislodged or dropped does not fall vertically downward, but instead acquires a drift counter to the rotation direction which is larger if it starts closer to the axis of rotation (or away from the floor). An object thrown at arbitrary angles follows highly unusual trajectories which depend on the height above the floor at which the object is thrown, the direction thrown, and the angular speed and radius of the space station. Performance of ordinary tasks which require skill in manipulating moving objects (such as hammering a nail) must be re-learned in rotating environments. An astronaut or any object moving in the direction of rotation is heavier than when at rest, and the weight change depends on the speed of movement. He is correspondingly lighter when he walks in the opposite direction. Crew and equipment movements near the center of rotation are particularly affected by rotation phenomena.

These effects are all reduced as the radius of the system increases and as the rotational speed is reduced. A design where the astronauts could carry out their activities at a radius of 150-200 feet from the center of rotation would produce a field with almost imperceptible rotation effects. A station this large would require a rotation rate of only about 3 revolutions/minute to provide a 1g field. In such a design, all of the above effects would become imperceptible, so that these objections to artificial gravity would not apply.

2. The gravity gradient in rotating systems is expected to have two long-term physiological effects:
   a) Since gravity strength is larger toward the floor, the leg bones would gradually thicken at the expense of those in the upper parts of the body.
   b) Body fluids, (expecially venous blood) would be distributed differently than in a uniform field and would pool to a lesser extent. This would change the cardiovascular reflexes in a way similar to the effect of zero-gravity but less extensively.

3. Rotating space stations which are in operation for more than about 90 days will need re-supply of crews and supplies, which implies docking to the rotating station. This could be done by spinning the incoming vehicle before docking, or by landing on a counter-rotating hub which is fixed in space. To avoid crew motion sickness, the spin up procedure should be carried out gradually over a period of several days. The engineering problems of both docking methods are severe. In the first case there is a difficult guidance problem and in the second case an elaborate hub must be designed for counter-rotation at variable speeds. The space station configuration becomes even more complicated if zero-gravity experiments are required to proceed uninterrupted during docking. This would require a third section which continuously counter-rotates independently of docking operations.
4. In constantly-rotating environments, the semicircular canals are abnormally stimulated when the man moves his head. The response depends on the rotation speed of the space station, the magnitude and speed of head tilt, the frequency of tilts, and individual susceptibility. The vestibular organs have significant neuro-anatomical connections to the reticular system dealing

with alertness and attention, to the eye muscles, to the autonomic nervous system dealing with regulation of respiration, heart rate, GI tract motility, etc., to voluntary body muscles, and to the cerebral cortex. If these head tilting movements are carried out long enough all normal individuals manifest motion sickness symptoms ranging from decreased alertness, voluntary restriction of physical activity and oculomotor impairment through nausea and vomiting, and prostration. The problem then remains to determine a gravity level adequate for habitability, a radius suitable for the structural engineer, and an rpm to which crewmen can readily adapt with tolerable semicircular canal side effects.

PAST MEDICAL APPROACH

With respect to crew performance and locomotion, Crew Systems Division studiew at MSC as well as other investigations utilizing aircraft flying parabolic trajectories for the production of "zero" or subgravity have documented the fact that zero gravity work task efficiency is improved when a gravity level of over 0.3g is provided. These studies suggest that 0.2g is not an acceptable level while 0.5g does not appear substantially superior to 0.3g for such things as locomotion, water pouring, and nut-and-bolt torqueing, etc. These levels may even be superior to Earth gravity for certain tasks.

No semicircular canal measurements have been made to date on U. S. astronauts in flight. The extremely high rotation rates accidentally produced during Gemini VIII (March 16, 1966) lasted for only a few minutes. During this period the crewmen reportedly experienced the normal disturbing reactions to head movements that they were required to make in the operation of their spacecraft. The relatively high angular velocity, the brief duration, the short distance from the center of rotation and the annecdotal nature of the "measurement" of psysiological responses severely limit the applicability of knowledge from this incident to rotating space stations. Pre-, in-, or post-flight canal measures were not obtained thus preventing any correlation of stimulus with response. The Gemini XI and XII missions involved slow rates of rotation which were far below those required for a useful artificial gravity. The rotation rates were reported to remain below threshold for vestibular detection for the duration of the rotation phase of the flight.

PRESENT MEDICAL POSITION

Artificial gravity cannot be justified, however, solely as a physiological support requirement because no definite clinical evidence now exists indicating that man would not be able to tolerate prolonged exposures to weightlessness.

In the event that artificial gravity should ever be planned, the rotating system parameters will probably be within the design envelope in Figure 1, although sufficient information does not now exist for choosing a combination of radius, rotation rate and g which will ensure acceptable vestibular adaptation.

The assessment of the anticipated benefits of an artificial gravity and the determination of its optimum magnitude and concomitant angular velocity, will require that standardized measures be obtained on selected astronauts during separate weightless and rotating flights. Ground based centrifuge and bed rest studies alone cannot provide the required information.

A reduction in the severity of the vestibular side effects of rotation occurs if the crew is gradually acclimatized to the space station rotation and if they have had preflight centrifuge experience. Each of these factors deserves careful consideration from both biomedical and operational viewpoints. For example, the following typical questions must be answered. What is the most rapid tolerable spin up time? Will restriction of head movements in order to prevent acute canal symptoms interfere with or lengthen adaptation? How long will vestibular suppression or adaptation acquired on a preflight centrifuge persist? For how long and how soon before launch must a crew receive centrifuge experience, if at all? Is such "pre-adaptation" feasible from a crew-time standpoint?

It is clear that duplication of the rotation-in-space condition with alignment of "gravito"-inertial force with plane of rotation is not possible with centrifuge facilities under earth's gravity. The significance of this difference and hence the degree to which ground rotation studies can later replace inflight studies will remain unknown until manned vehicle rotation is achieved in space.

FUTURE EFFORTS

In general, no information of real prognostic value is available to the biomedical community at this point in time. The program outlined below is considered to be technologically feasible and sufficiently comprehensive to provide those experimentally derived conclusions required of a durable space effort.

a. Development of a standardized series of measures for both inflight and ground use:

   (1) Sensory motor performance tests

   (2) Work task efficiency tests

   (3) Semicircular canal thresholds

   (4) Rotation sickness susceptibility test

   (5) Otolith organ sensitivity test

   (6) Cardiovascular function tests

   (7) Musculoskeletal assessments

b. Administration of these tests to the entire astronaut population no more infrequently than semiannually, with a view toward gathering a normative data bank over a period of years.

c. Additional pre-and postflight administration of these tests to all astronauts who fly on any mission; inflight administration during biomedical missions.

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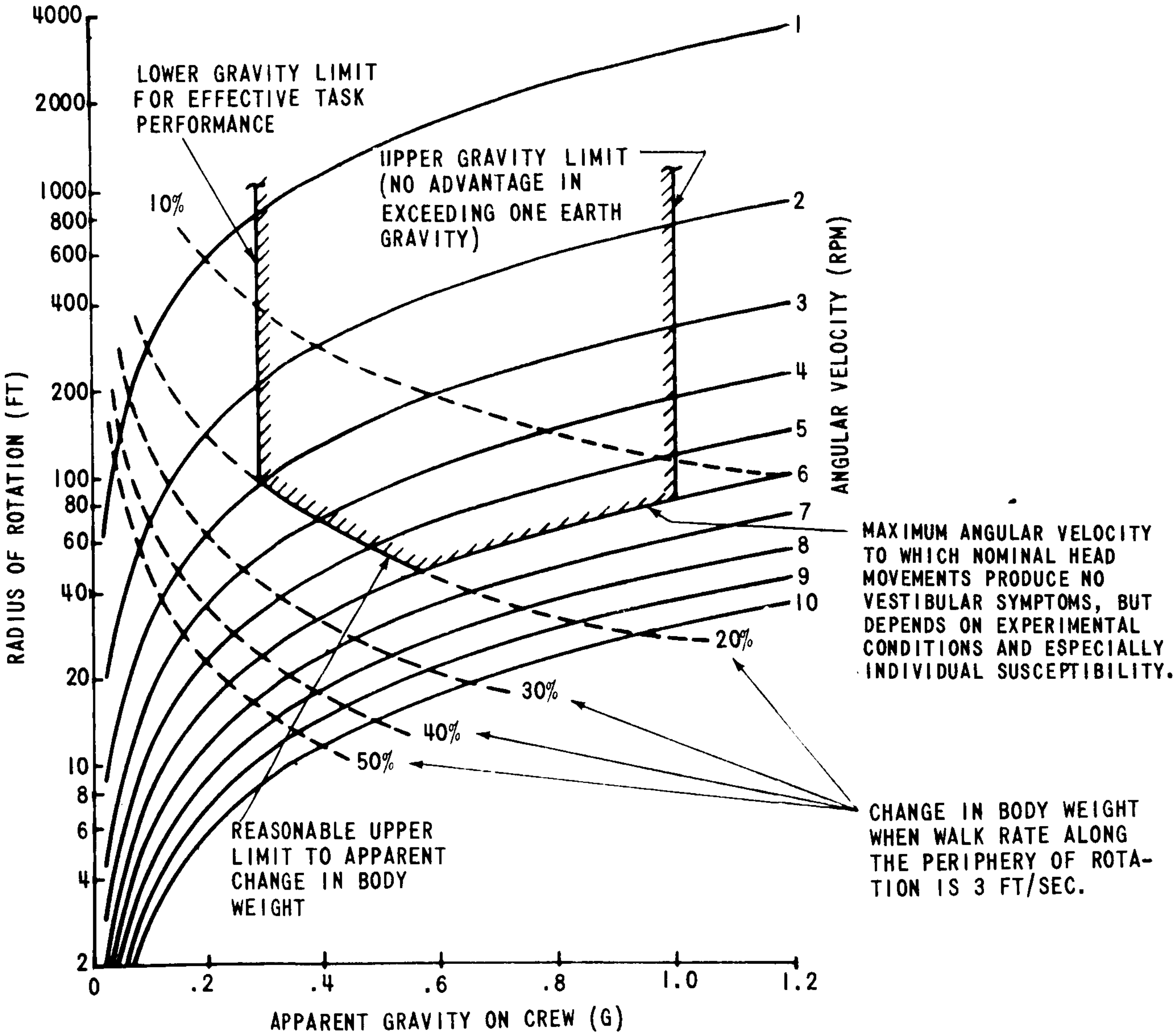

FIGURE 1 - PRELIMINARY TOLERABLE LIMITS FOR ACCEPTABLE HUMAN PERFOFMANCE IN ROTATING SPACE SYSTEMS

CLINICAL MEDICAL CARE

STATEMENT OF THE PROBLEM

Manned space flight programs to date have yielded information indicating that inflight stressors may produce physiological or performance decrements in man. In addition to these, many spontaneous pathological states (disease or injury) may also develop during a mission. Consequently, medical problems which have significant relative risks of impairing mission completion must be identified and the capability to prevent and/or diagnose and treat these conditions in-flight must be developed.

For example, the relative risk of crew incapacitation due to the development of spontaneous disease is only moderately well known, and this in the context of certain Earth-based populations to which varying selection criteria have been applied. Epidemiologic data on pertinent selected populations will be required for prediction of the incidence of significant medical problems arising from endogenous factors.

PAST MEDICAL APPROACH

Astronaut Selection Criteria

Physical standards applied for the selection of astronauts have evolved from military experience in selecting pilot trainees. Further selection of pilot-astronaut candidates has occurred through various phases of military flight training, military flying and test pilot experience. Scientist astronaut candidates have gone through analogous selection primarily on an academic basis and, therefore, they do not represent a homogenous, highly selected population in regards to physical qualifications for space flight.

Inflight Clinical Monitoring

Flight qualified aids in diagnosis consist of verbal reporting of subjective feeling by radio, body temperature, respiration rate, electrocardiogram (sternal and axillary leads), electroencephalogram, and blood pressure. Flight qualified treatment capability is limited to verbal advice to the crew by radio and to a medical kit containing a relatively small number of medications and first aid items.

PRESENT MEDICAL POSITION

Preventive Medicine (Preflight)

Initial astronaut selection criteria must be continually updated as more knowledge is gained concerning the effects of space flight factors upon pre-existing physical conditions. Mission specific flight crew selection criteria should take into account all possible predictors of the individual's state of health relative to the specific mission duration and expected space flight stressors. These should include correlation of age-space epidemiological data, from closely analogous populations, with the individual's past history, including family medical history and detailed psychological, physiological, and physical examination data collected since the time of initial selection. These data must be of such a nature as to allow detection of trends indicative of aging processes or disease precursors. Acquisition of these data will require that complete physical examinations be accomplished semiannually, with shorter intervals between the times of collection of certain baseline data characterized by wide "normal" ranges. Current plans for the inclusion of appropriate stress testing in the physical examination protocol constitute an important requirement in providing these data. The clinical medical data management system currently under development in the Flight Medicine Branch must be fully developed to provide the capability for collection and collation of all physical examination data, physiological monitoring data, and pertinent environmental exposure data for each astronaut.

Certain measures such as dental restorations and prophylaxis will obviously contribute towards decreasing the risk of medical problems occurring during a long-term mission. Prophylactic measures against other categories of disease, such as appendicitis, will depend upon determination of the relative risks involved in a specific mission.

Inflight Diagnosis

Crew medical skill requirements are mission specific. For example, Earth-Orbit missions permit return of the crew to ground-based medical facilities early in the course of any disease process, but this will not be posssible for missions in non-orbital trajectories. Onboard medical skills and resources must be fully capable of coping with mission threatening medical problems. It appears that a physician-crewmember is desirable for extended space flight in Earth orbit and required for long-term non-orbital missions. He should be thoroughly familiar with all aspects of aerospace medicine, have extensive clinical experience, training in diagnositic and therapeutic procedures and possess basic dental and surgical skills.

Weight, volume, and cost will undoubtedly limit the amount of diagnostic equipment to be carried onboard. Every effort, however, should be made to provide the physician-crewmember with an adequate broad-range diagnostic capability. Flight qualified equipment should include physical examination instruments and a laboratory facility which will allow basic X-ray, urinalysis, hematology, blood and urine chemistry, and bacteriology procedures.

Data handling requirements and priorities for Earth-orbital flights and long-term deep space missions will differ. In the first situation transmission of biomedical data to ground-based experimenters, in sufficient quality and quantity to allow observation of trends, will be necessary in order to define precisely the physiological effects of the space flight factors under study. In the case of long-term deep-space flights, the onboard physician must have as much information as possible to assist him in making the correct diagnosis should medical problems develop. Although he will have voice consultation capabilities (continuous or intermittent) with Earth-based medical personnel, his ability to cope effectively with contigencies will depend on both his experience and the availability of onboard clinical data processing and display resources.

Inflight Medical Treatment

The selection of treatment methods will depend upon the possible pathological manifestations predicted for a specific mission, upon selection of the most appropriate form of therapy consistent with up-to-date medical practice, and upon the applicability of this therapy to the space flight situation. All treatment methods proposed for inclusion on long-term manned missions must be tested and verified in Earth orbit before their incorporation into the operational protocol.

FUTURE EFFORT

Detailed epidemiological studies of the astronaut population itself and of highly selected analogous populations must be conducted to allow better reliability in the prediction of spontaneously occurring medical and dental problems. These studies should include data obtained under closed ecological conditions.

Medical procedures, clinical equipment and physician-astronaut training requirements must be studied and developed to make inflight medical care both possible and effective. On line analysis and displays of important parameters should also be emphasized along with semi-automated diagnostic techniques. In addition, certain animal studies will undoubtedly be required for both ground-based and inflight verification of certain therapeutic procedures.

DATA MANAGEMENT

STATEMENT OF THE PROBLEM

Data management might be arbitrarily defined as that portion of any organization that performs a service function of acquiring and redistributing quantitative or qualitative information considered useful in meeting the goals of the organization.

Ideally, the individual flight surgeon or scientific research worker handles his own data management problems. He acquires his data directly from instrumentation he has constructed, describes his results, and determines his future activity on the basis of his interpretation of these results. In practice, this simple approach is rarely possible for a variety of reasons. Highly specialized equipment, technically trained individuals, and elaborate procedures intervene between the medical or engineering problem and its solution. Such intervening complexity usually increases with the breadth and nature of the goals, the size of the organization, and the responsiveness required. The objective of this data management program is to develop a flexible, comprehensive data collection and handling system that will meet the individual and collective needs of all the inflight medical programs described in this document. This can be accomplished by providing:

a. Improved descriptive, inferential and predictive capability for real, near-real, and non-real time safety monitoring.

b. More systematic handling of all MSC biomedical data including the standardization of MSC biomedical data, the consolidation of file information within the Medical Directorate, and periodic feedback.

c. Improved data acquisition capability for both operational and experimental use.

Major problems affecting the selection of an optimal data management system are these associated with on-board data processing for extended missions and organizational support. These factors are considered in greater detail below.

On-Board Data Collection Equipment

A minimum data management program must provide valid, reliable, and accurate medical instrumentation to measure physiological, environmental, and psychological factors of interest. Correct medical assessment during prolonged manned missions is critical and cannot be done with generally inadequate instrumentation. To obtain quality medical instrumentation within the constraints of extended spaceflight is quite difficult and over-simplification is not uncommon. For example, reliability of almost any acquisition equipment for two years will pose difficult problems--many of which will be solvable only by maintenance and repair capability.

The two classes of inflight instrumentation needs for the biomedical program are safety monitoring instrumentation and medical experiments instrumentation. At any given time these can be in any one of about six stages: undefined or in definition stage, in prototype stage, in contract procurement stage, in production stage, in flight qualifying stage, and in flight readiness stage.

All inflight instrumentation must go through most of these stages requiring long lead time and extensive coordination. A major problem that will become increasingly important during extended mission is how to become more responsive to changing instrumentation needs.

One method is to look three or four missions ahead, obtain the individual and collective instrumentation needs, and go through the stages mentioned above.

Another method is to define a general and standard acquisition system that should handle a high percentage of all inflight instrumentation needs for an entire NASA program. In effect, this calls for flight qualifying a "standard laboratory". This method has received considerable contractual study.(1,2)

Advantages and disadvantages exist for both methods and each will require technical trade-offs in terms of scheduling, costs, reliability, accuracy, flexibility, other on-board systems, weight, etc. (3,4,5) The two methods are not mutually exclusive since some percentage of instrumentation will not be available in the "standard system". Regardless of the method chosen, extended missions will necessitate a much greater in-house responsiveness and/or stabilization of medical instrumentation.

Telemetry Management During Extended Missions

Having acquired the highly specialized data necessary to monitor the crewmen involved and to complete medical research, another major problem will be its timely return to earth for interpretation and mission management support. Assuming manned planetary missions, distances will be millions of miles (while the limiting speed of light will be in thousands of miles per second) and communication links with the ground are expected to be intermittent. Consequently, real-time earth monitoring will not be possible. With this in mind, greater dependence on ground-based mission management support will not be possible and results must be displayed for interpretation by crewmen. Nonetheless, considerable data must be transmitted for more specialized ground analysis.

Aside from telemetry considerations associated with distance, there are those arising from the volume of medically relevant data to be transmitted. Some balance between ground and on-board data management systems will be necessary to deal with the volume of medical data since all of the raw data cannot be transmitted nor stored on-board. Both the telemetry and spacecraft constraints will make some degree of on-board data compression, selection, or analysis mandatory.

In general, the ultimate degree of on-board compression will involve highly technical developments and trade-offs which are currently under investigation by many engineering offices of NASA. Either the telemetry capacity and telemetry coverage must be increased (6), the on-board data management system made more flexible via on-board computers (7), or some combination will be needed.

Data Processing for Extended Missions

Since biological organisms characteristically display much individual variability and adaptability, a considerable amount of data must be processed to establish non-chance trends for any physiological subsystem. As mentioned earlier, one of the major problems in extended missions will be the degree that this data processing must be accomplished by an on-board system as opposed to a ground-based data processing system.

Aside from acquiring the data from various instruments, an on-board data management system would have many control functions. Requirements exist from other content areas of this extended mission biomedical program for on-board analog to digital and digital to analog displays, for on-board data logging, for accurate experiment calibration control, for on-board data reduction, for temporary storage and for accurate dump capabilities.

Similar capabilities will be needed for at least one ground-based system to both develop and check-out any on-board system and to provide ground support for data processing that cannot be completed on-board. In addition, marked increases in ground based pre-flight data processing associated with baseline, validity, and reliability studies must be anticipated.

Organizational Support

Three broad organization problems exist in the selection of an optimal biomedical data management program for extended missions. One problem relates to integrating medical data needs with other scientific or operational needs, another is related to adequately communicating specialized medical needs, and the last relates to contractual support.

It is frequently not understood that MSC is an engineering community with the primary task of managing all manned missions. To meet such responsibilities, MSC has established a wide variety of inter-acting data management systems. Each of these have their own subgoals, policies, restraints, procedures, equipment, and personnel with multiple coordination and dependence being required. In short, the biomedical data management program for extended missions must be integrated with other planned systems. An independent medical system would produce redundancy in equipment and personnel, imcompatability, and less responsiveness to the total mission. On the other hand, the extended mission medical subsystem chosen must meet all of the unique aspects related to medical problems.

Frequently, the approach taken in medical research is different from engineering research where destructive testing, greater experimental control, etc., is possible. Additionally, much of the information needed to assure crew safety during long periods of space flights is clinical and not yet quantified. Such problems frequently make communication and implementation difficult. Extended missions will require more depth in intermediate personnel to assist in translating medical requirements into engineering and analytical languages.

Finally, extended missions will require considerable ground based research to meet a variety of needs. One class of contractual support is for those utilizing highly specialized analytical techniques for a particular scientific experiment. Another class is for technique validation studies: Evaluating alternate methods or techniques, developing and testing physiological models, etc. Baseline collection support for medical experiments or operational use is still another class of contractual support having direct relevance to data management needs. Finally, contractual support to obtain better inter-center and inter-agency support will be needed since others will frequently have useful data management techniques applicable to extended mission needs.

PAST MEDICAL APPROACH

Mercury and Gemini Data Management

The primary medical goal of these programs was to assist in ensuring the safety of the astronaut by providing adequate clinical medical care in an unknown situation. This medical care was based primarily on the experience and research of flight surgeons with the most relevant experience of aviation medicine. Inflight human research was a major secondary goal.

Because no one could say with certainty what reactions man would have in a weightless environment, the data management acquisition strategy in the Mercury program was to obtain the maximum amount of raw data. This strategy required about 75% of all the spacecraft to ground data and, because of remote-site telemetry limitations, the data had to be converted to analog for return to Houston. The Gemini medical experiments data management acquisition strategy was similar in that all raw data was recorded onboard in analog form and returned post flight. Except for noise, phase shifts, and timing problems, this strategy worked well and met most of the medical goals.

Since the best medical experience involved careful clinical judgments of analog stripchart recordings, the flights were short and a fair percent of the data was noisy, the data management processing strategy was to put all data on strip-chart recordings. This strategy resulted in meeting the primary clinical goals within a difficult time frame and with very little capital investment. In general, the goals for experiments were met by sophisticated contractual processing of on-board tapes with very little in-house capital investment.

Despite this achievement, it became obvious that such an approach could not handle even the operational Apollo needs--aside from those foreseen for AAP and beyond. Such a system is, in effect, a listing of the raw data on a piece of paper! It is cheap and informative, but its limitations are painfully obvious as volume and complexity of data grows.

Current Apollo and AAP Data Management Efforts

No attempt will be made in this discussion to provide a complete summary of the operational changes made for the Apollo program as they remain dynamic and the reader can obtain this from other documented sources (8, 9, 10, 11, 12a, 12b). Instead, a brief synopsis will be given as to where we reasonably expect to be operationally at the end of Apollo and early AAP.

With respect to on-board data collection equipment, no major changes beyond the current electrocardiographic and pneumographic equipment are expected during Apollo. By the end of early AAP, flight qualified equipment will be available to meet the needs of approved AAP medical experiments. Description of the current qualified equipment is given elsewhere (13) and description of expected AAP instrumentation is given in the Experiment Implementation Plan (EIP) for each experiment. In short, very little flight qualified bioinstrumentation is likely to be available for extended mission support.

With respect to telemetry, the Apollo system is effectively the same as Gemini except that the latter transmitted more information per man. During later Apollo, improvements in accuracy are likely. During early AAP, more varied medical information will be transmitted and greater accuracy can be expected. In brief, the existing telemetry system will be taxed to handle AAP and could not support more medical requirements for extended missions.

With respect to Apollo ground-systems data management support, improved capabilities have been implemented for mission support, for chamber testing, and for laboratory support (8, 10, 11). Additional support for AAP will be requested and, if approved, these evolutionary improvements should provide the necessary ground-support for extended missions.

PRESENT MEDICAL POSITION

To support the biomedical data collection and data handling during extended space missions:

1. An on-board data management system such as the Integrated Medical and Behavioral Laboratory Measurement System (IMBLMS)* or its equivalent will be required. Since the ultimate configuration can be expected to change with time, a primary criterion will be flexibility. Other criterion that will be included or considered for an on-board data management system are given in Table 1.

2. A ground-based data management system will also be required to correlate extensive data from ground tests of the astronauts and systems with in-flight data collected during the mission.

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*Refer to PART I - Program Summary, IMBLMS

3. The data management program must extensively coordinate the medical activities with the other engineering and operational activities at MSC and during long-duration flight. This involves, a) informing the medical personnel of the possibilities and limitations of present-day data handling techniques, b) assisting them in understanding and formalizing their data processing needs, and c) designing the system to accommodate the unique requirements of the biomedical program.
4. All manned tests and flights will use magnetic analog tape recordings of the medically-important raw data. This recording will be done in a standard recording format (subject identification, channel assignment, etc.) to be stored and retrieved in a consistent manner by the Medical Directorate.
5. All biomedical data will be standardized in a way useful to the principal investigators and mission planners.

FUTURE EFFORTS

Ground Based R & D

1. Prototype IMBLMS systems from two separate contractors will be available at the end of this fiscal year. Operating characteristics, in terms of both hardware and software, will be evaluated, trade-off and failure analysis studies conducted, and the best features from each contractor incorporated for building and flight qualifying a single integrated modular system.

2. Validity and normative studies employing the IMBLMS prototype systems will be conducted to verify that the measurements are appropriate and to establish their normal or emergency ranges.
3. Engineering studies will be conducted to verify that the proposed system will have sufficient flexibility to fit into a wide variety of proposed spacecraft configurations.
4. Standardization, integration, and automation of ground-based medical systems will continue so that a medical data base will be available to evaluate medical systems improvements.
5. New analytical techniques will be evaluated for applicability to extended missions. Adaptative analytical techniques and those simulating multivariate "clinical" judgment will be given special attention.

Inflight and Simulation Checkouts

In order to determine the optimum division of work between extended missions on-board data management and the ground-based data systems, various simulations will be performed. The ultimate test of the data management configuration chosen will be its overall performance during spaceflights. Individual components will be evaluated during and after flights of increasing duration and modular changes made as required.

Such efforts should result in on-board and ground-based data management systems capable of meeting the criteria in Table 1 and in meeting the operational and experimental needs of extended manned space exploration.

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TABLE I

DATA MANAGEMENT SYSTEMS CRITERIA

I. SYSTEMS CRITERIA -- DOES THE SYSTEM HAVE:

1. MULTIPLE AND FLEXIBLE INPUT-OUTPUT CAPABILITY?
2. VARIED, EFFICIENT, AND USEFUL ANALYTICAL PROGRAMMING CAPABILITY AT THE DESCRIPTIVE, INFERENTIAL, PREDICTIVE, AND INTERPRETATIVE LEVELS?
3. MODULARITY AND ADEQUATE EXPANSION PROPERTIES?
4. VARIED DATA COMPRESSION CAPABILITY?
5. ADEQUATE STORAGE CAPABILITIES (TAPES, CORE, DISK)?
6. CAPABILITY FOR IMPLEMENTING CHANGES EASILY?
7. FLIGHT QUALIFIABLE HARDWARE?
8. VERSATILE SEARCH AND SELECTIVE EXTRACTION PROPERTIES?
9. ANALOG (A) TO DIGITAL (D) AND D-A CONVERSION?
10. EFFICIENT MONITORING AND ERROR MESSAGE PROGRAMS?
11. MULTIPLE, FLEXIBLE, AND READABLE DISPLAY PROPERTIES?
12. RESPONSIVENESS TO MULTIPLE USERS?
13. EFFECTIVE INTERRUPT CAPABILITIES?
14. ADEQUATE OPERATIONAL AND MAINTENANCE DOCUMENTATION?
15. REPAIR AND/OR BACK-UP CAPABILITY?

II. OPERATIONAL CRITERIA -- FROM USER'S VIEWPOINT, IS THE SYSTEM?

1. EASY TO LEARN, USE, CHECK, AND REPAIR?
2. INFORMATIVE AND TIMELY?
3. INTERESTING TO THE USER?

III. ORGANIZATIONAL CRITERIA -- DOES THE SYSTEMS ORGANIZATION PROVIDE:

1. LONG RANGE ADMINISTRATIVE AND MONETARY SUPPORT?
2. INTERDISCIPLINARY SERVICES?
3. COORDINATION AMONG INFORMATION SOURCES?
4. INTEGRATION WITH OTHER PLANNED DATA MANAGEMENT SPACECRAFT SYSTEMS?
5. PERSONNEL WITH TIME TO IMPLEMENT, SERVICE, AND IMPROVE SYSTEMS?
6. WELL DEFINED AND LIMITED STAGES TO REACH ULTIMATE GOALS?

SIMULATION

STATEMENT OF THE PROBLEM

Reduced to essentials, the purpose of simulation is to provide a tool for the acquisition of knowledge under circumstances where the acquisition of that knowledge from the original source would be impracticable. The reason for the impracticability may lie in economics or safety, or in the fact that variables cannot be adequately controlled. It is not economical to build a progressive series of spacecraft, systems, or subsystems as design and development proceed, nor is it economical or safe to use production craft for crew training. Thus, it has become necessary to build a variety of simulators to provide basic data under controlled conditions.

Simulators are used in situations in which basic knowledge is weak; in which complex interrelationships are not fully understood; and in which calculations, estimates, or judgements cannot be made with sufficient confidence.

Simulation has had a large place in manned space mission systems, specifically in relation to engineering design; evaluation and validation of concepts, materials, and man; development of procedures; and training. It is perhaps not surprising that in the literature the most important uses of simulation cited by an author appear to vary with his background discipline.

To the design engineer, a simulator is largely a device to provide him with data for this design studies. To the human factors engineer, simulation is a means of determining optimum displays and cabin layout. To the environmental test engineer, it is a method of testing the integrity of systems, subsystems, and components under hazardous environments. To the aerodynamicist, it is a way of examining the dynamic stability of a system under flight conditions. To the environmental physiologist, simulation is a tool for testing man's response to stress. To the psychologist, it is a system for measuring man's performance. To the instructor, it is a sophisticated training aid, and so on. Many authors have tested uses and potential uses of simulators in manned space flight systems, and the compilation shown in Table 1 was synthesized from them by Frazer (NASA SP-102)

It is clear that a distinction must be made between simulation for training and simulation for research, and, in the research field, a further distinction between operational or engineering simulation and psychophysiological simulation must be made. The purpose of operational simulation is to determine the extent to which the machine system is modified by placing man into the loop, the aim being to optimize the combination. The object of psychophysiological simulation is to study the effects of the man-machine environment on man.

PAST MEDICAL APPROACH

The art and science of simulation has evolved out of necessity as a tool for the invesigation of situations, tasks, and problems which, for various practical reasons, could not be examined in the actual mission context. Although such simulations have application, in one way or another, to almost all the sciences - physical, human, and social - they have found particular application in the investigation of engineering and psychophysiological problems of space flight. Starting as a technique for the simple representation of the essential elements of a problem, it took a giant step forward with the development of electronic, optical and computer sciences, particularly with the mating of the analog and digital computer. These same developments, however, have introduced a new problem in that with the use of sophisticated technology it is possible to simulate, with remarkably apparent realism, environmental and other situations, the parameters of which may be incomplete, open to unknown bias, or merely speculative. Basing measurements and observations on such simulation is hazardous.

It is necessary then to reemphasize certain principles which perhaps can tend to be overlooked by those who naively consider that simulation will provide a solution to most of their problems. These principles may be stated as follows:

(1) A situation, task, or problem can be simulated in a valid manner only insofar as its parameters are known. This was clearly demonstrated when the simulations for the early Gemini extra-vehicular activities (EVA) did not adequately predict the difficulties which were encountered by the EVA crewman. Improved techniques using neutral buoyancy water simulations, together with more carefully

planned time lines, demonstrated the capacity of an EVA man to perform useful work.

(2) A simulation can provide the solution to a problem or provide valid information, only if the elements of the solution of the problem reside in that simulation.

(3) Simulation may provide an incorrect solution or false information if the simulation is incomplete or the parameters of the simulation are incorrect.

(4) Only those parameters of a situation, task, or problem necessary for completeness of the simulation need be represented in the simulation.

Within these bounds, simulation has been a valuable tool in the investigation of, and preparation for, manned space flight, although there must always be the cautious observation that because of recognized lack of knowledge, or what is worse, unrecognized lack of knowledge, the simulation may be incomplete. It may be equally difficult to determine what parameters to simulate. The resulting choice may be arbitrary, in which case the final simulation and, accordingly, dependent measurements, may be biased.

PRESENT MEDICAL POSITION

The four principles outlined in the previous section must be kept firmly in mind when a specific simulation is contemplated. For the general case, previous experience in the large number of applications of simulation to manned space flight has resulted in the establishment of a series of practical guidelines for its use.

1. Full scale simulations will be conducted for purposes of training and checkout of combined spacecraft and ground support systems and personnel. Total simulations, conducted on a simulation day for each planned mission day will not be performed. Biomedical systems and hardware requiring high reliability for the entirety of a mission shall be tested by overload and destructive testing techniques to yield required data.

2. Simulations involving flight crews shall be conducted for training and personal evaluation purposes. The duration of such simulations will be only that required to produce proficiency in a single phase of the mission. Subsequent simulations will be fitted to the particular requirements of other phases. Other useful data which can be obtained during such simulations, must be acquired whenever possible.

3. Baseline data simulations involving the crew shall not be conducted. This does not specify that control data on

each individual crewman is not necessary, but that simulation data may not be control data and may relate only to an Earth-bound artificial set of conditions. Baseline control data shall be obtained under controlled conditions during periods of normal Earth-based activities.

4. Research studies shall be conducted. The subjects utilized will depend upon the nature of the information desired from the study.

5. When long-term effects are to be studied, the experimental design shall be such that predictive models are used or generated by the study. Space missions themselves shall provide data for model verification. A day-for-day relationship shall not be considered for durations longer than six months except under very special circumstances and then only by the presentation of evidence that no other means of obtaining the information is at hand. Space mission exposure itself shall be the test bed for changes requiring longer than six months exposure for detection and prognosis. These shall require adequate in-flight monitoring or measurement instrumentation. To provide on-the-spot diagnosis, to institute therapeutic measures and to manage experimental procedures, it shall be the policy to require a physician/scientist astronaut as a crew member for all missions of six months duration or longer.

FUTURE EFFORTS

Review of several contractual efforts which were conducted on a twenty-four hour basis has indicated an overall cost ranging from \$500 to \$10,000 per subject day of data. The operating costs alone (which are less than 50 percent of the total contracting costs) for one chamber facility (capable of accommodating only four subjects) are \$700 an hour. Information on ten subjects for a continuous period of 180 days (1800 subject days) would cost in contracting funds alone between \$0.9 million and \$18 million. Added to this must also be the cost involved in the budgeting, procuring, monitoring, and auditing functions required of the Government by such projects. From a cost effectiveness point of view, therefore, day-for-day simulation for long term missions is not feasible.

Intangible costs which must be considered are the effects of long duration studies on the subjects themselves, not only their health but additionally, the effect upon their future by the loss of two years (if study day must match mission day) for a Mars mission simulation study. It should not be necessary to simulate an entire planetary mission, particularly when extended earth orbital experience is gained and the psychophysiological and technical areas have acquired the necessary competancies. It can be categorically stated that, in the design of manned space vehicles and the preparation for manned space flight, simulation, when properly used, will make many contributions to the biomedical areas of psychophysiological research, familiarization and training, and selection of astronauts. To expand simulation to its full potential, the future efforts must be directed towards illuminating those critical factors which determine whether a particular simulation has adequate fidelity without the expenditure of excessive resources.

The following sections detail the main facets of simulation which must be well understood by practitioners of the art, and which require a continuation of the development work in progress.

1. Proper usage of simulation is predicated upon adequate knowledge of the parameters to be simulated; development of a careful experimental, training, or selection, protocol; and selection of a suitable simulation system which will represent the required parameters with necessary fidelity.
2. Obtaining an adequate knowledge of the parameters entails careful analysis of the task or tasks to be simulated; the environment in which they are to be simulated; and an examination of the potential interactions occurring in man, task and environment. Much information required for this purpose, particularly for future space mission, is ill-defined and subject to guesswork. Simulation based on assumed or extrapolated parameters may well be invalid.

3. When the parameters are known, the value of simulation depends on the fidelity with which these parameters are represented. Fidelity may be both physical and psychological. Difficulties in achieving psychological fidelity may be reduced by using the concept of perceptual fidelity, or phenomenal equivalence, in which illusions of realism are created.
4. For the conduct of operational and psychophysiological research, physical fidelity and actual reproduction of the critical parameters are necessary. For training and selection, perceptual fidelity can often be used to provide an acceptable transfer of training.
5. It is unnecessary to reproduce all the parameters of a given situation; only those parameters necessary for completeness of the simulation need be represented in the simulation. These parameters, however, are frequently not fully known.
6. Selection and representation of critical parameters may include a known or unknown bias which can invalidate the resulting simulation.
7. For a manned space simulator, requirements for physical fidelity in cabin layout, for working realism in displays and consoles, and for control feel and

display relationships have not been thoroughly investigated. Work on similar requirements for aircraft simulators suggests that realism in these parameters may not be vital for adequate transfer of training. Much work is required to determine the necessity for realism in this area.

8. Motion simulation, in part-mission or whole-mission simulators, seems necessary only where the effects of motion are under investigation or where motion affects performance. The latter situations are not fully defined. There is no definite evidence as to whether, in training, motion cues should be incorporated into a full mission simulator or whether adequate transfer of training can be provided separately on a simple simulator designed for the purpose. Perceptual equivalence of motion is of value in visual displays for rendezvous and docking, and perhaps landing, simulators. Because of proprioceptive and vestibular feedback in terrestrial gravity, simulated motion may contribute to negative transfer of training.

9. The requirement for representation of external vision in a space-cabin simulator depends on the nature of the task or tasks to be accomplished. There appears to be no need to recreate the entire visual world in

any given area, nor is there a requirement to provide a visual simulation for all aspects of a space mission. Facilities are required for presentation of displays governing terrestrial, celestial, and lunar or planetary observation at specific times during the mission, for rendezvous and docking, and for terrestrial or other landing operations. These facilities will be used for detection, recognition, navigation, and monitoring of vehicle control and extravehicular activity. Color presentations appear useful but not essential.

10. The duration of simulation required to validate a mission is not known. With prolonged missions (beyond 3 to 6 months) it will no longer be feasible to simulate a mission in its entirety. Much work is required to determine if there is a consistent ratio relating the duration of a mission to a lesser duration of useful simulation of that mission. If there is no such ratio, arbitrary decisions on the suitability of the mission will have to be made on the basis of other evaluations of man's capacity to tolerate single or multiple stresses.

11. The question of transfer of training accruing from part-task versus whole-task training has not been resolved. It would appear that where a whole task

can be discriminately analyzed into specific component parts, at least some of these can be successfully taught with a part-task simulator. Unification of the components might thereafter be developed on a mission simulator, provided that its applicability has, in turn, been experimentally validated.

12. In all cases, verification of a simulator system's suitability is necessary to determine its validity. Verification requires an experimental comparison of the simulator system with actuality. Where this is not possible, the results obtained from simulation apply only to the conditions of the simulator and can be applied to reality only with utmost caution.

TABLE I

USES OF SIMULATORS

I. DESIGN ENGINEERING
   A. DEVELOPMENT OF CRITERIA FOR:
      1. VEHICLE ENGINEERING
         a. STRUCTURAL
         b. AERODYNAMIC
         c. SYSTEMS
         d. SUBSYSTEMS AND COMPONENTS
      2. SENSOR, SIGNAL PROCESSOR, AND DISPLAY ENGINEERING
         a. RADAR
         b. INFRARED
         c. ELECTRO-OPTICAL, INCLUDING LASER AND TV
         d. ACOUSTICAL
      3. HUMAN ENGINEERING
         a. HABITABILITY
         b. INSTRUMENT AND INDICATOR DISPLAY AND OPERATION
         c. CONTROL DESIGN, LOCATION, AND OPERATION
         d. MAN-MACHINE INTEGRATION
      4. PERSONAL PROTECTIVE EQUIPMENT
   B. DEMONSTRATION OF CONCEPTUAL FEASIBILITY OF A DESIGN

II. EVALUATION OF SYSTEMS, COMPONENTS, AND MATERIALS
   A. VALIDATION OF DESIGN STUDIES
   B. DETERMINATION OF STRUCTURAL INTEGRITY WITH AND WITHOUT STRESS
   C. DETERMINATION OF PERFORMANCE OF SYSTEMS, COMPONENTS, AND MATERIALS WITH AND WITHOUT STRESS
   D. EVALUATION OF PERSONAL EQUIPMENT
   E. PREDICTION OF RESPONSE OF SYSTEMS, COMPONENTS, AND MATERIALS TO PROLONGED STRESS

TABLE I (CONT'D)

III. EVALUATION OF MAN'S CAPACITIES

A. DETERMINATION OF HUMAN CAPACITIES, PHYSIOLOGICAL AND PSYCHOLOGICAL LIMITATIONS, IN NORMAL OPERATING CONDITIONS AND UNDER STRESS

B. DETERMINATION OF PERFORMANCE AND PROFICIENCY OF MAN AND MAN-MACHINE SYSTEMS IN NORMAL OPERATING CONDITIONS AND UNDER STRESS

C. PREDICTION OF MAN'S PERFORMANCE UNDER, AND PHYSIOLOGICAL RESPONSE OF MAN TO, PROLONGED STRESS

IV. PROCEDURES AND REQUIREMENTS

A. ALLOCATION OF FUNCTION TO MAN AND MACHINE

B. DETERMINATION OF PERSONNEL REQUIREMENTS

C. DETERMINATION OF OPERATING PROCEDURES

1. ROUTINE

2. EMERGENCY

D. DETERMINATION OF MAINTENANCE PROCEDURES

E. DETERMINATION OF LOGISTIC SUPPORT REQUIREMENTS

F. DEVELOPMENT AND EVALUATION OF TACTICS

G. DETERMINATION OF WORK, REST, AND ACTIVITY SCHEDULES

V. SELECTION AND TRAINING

A. SELECTION AND CLASSIFICATION OF POTENTIAL AND PARTIALLY TRAINED ASTRONAUTS

B. DEVELOPMENT OF TRAINING PROGRAMS, DEVICES, AND STANDARDS

C. DETERMINATION OF AREAS OF SPECIAL TRAINING

D. INITIAL MISSION TRAINING FOR NEW ASTRONAUTS

E. PROFICIENCY TRAINING FOR EXPERIENCED ASTRONAUTS

F. SPECIAL TRAINING FOR SPECIAL AREAS

G. TRANSITION TRAINING WITH TRANSFER TO NEW VEHICLE

H. PREDICTION AND MEASUREMENT OF PROFICIENCY

I. EXPERIENCE IN STRESSFUL ENVIRONMENTS

J. TRAINING FOR GROUND HANDLING CREW

INTEGRATED MEDICAL AND BEHAVIORAL LABORATORY MEASUREMENT SYSTEM (IMBLMS)

RATIONALE FOR IN-FLIGHT MEDICAL INVESTIGATIONS

Physiological processes associated with accommodation and acclimatization of individuals exposed to the flight environment have been observed to occur during the early hours of exposure. Delayed effects may also occur and these may be more dramatic than those detected in the early phases of flight. The more subtle the change, the more difficult its measurement; the more delayed the observation, the more difficult its interpretation.

It is not safe to judge at this time the relative importance of early or delayed changes with respect to the overall deterioration of the medical/behavioral performance capabilities. It can be said, however, that if the opportunity to make observations continuously throughout the flight is not afforded, valuable data will be lost and interpretation of subtle changes will be made more difficult. Judgement can be exercised in determining the frequency of measurements as observed changes become better understood and countermeasures, if required, are developed to reduce or reverse changes of a deleterious nature.

It is the position of the Medical Research and Operations Directorate at the NASA Manned Spacecraft Center that the critical in-flight biomedical/behavioral measurements identified under "Overall Positions and Objectives", are required to assure success in long-term future manned missions. The basis of this position is the fact that physiological changes have consistently been observed, which can reduce the overall capacity of man to cope effectively with the stresses of reentry and landing, as well as with the more stressful demands of in-flight emergencies. It is impossible in our present knowledge to describe the rate of onset of these deleterious physiological changes or to determine the relative importance of weightlessness as the primary causative factor. The in-flight medical experiments program will provide essential insight into the nature and extent of human acclimatization to the space flight environment in Earth orbit.

MEDICAL MEASUREMENT EQUIPMENT

Presently, the biomedical instrumentation available for flight use, consists of little more than vital-signs measurements, and as such is inadequate to flight-rate man for extended missions. As a direct result of this inadequacy, the office of Space Medicine, Manned Space Flight, NASA Headquarters, initiated the development of an Integrated Biomedical and Behavioral Laboratory Measurement System (IMBLMS) capable of accommodating approximately 150 measurements as part of existing and still to be proposed experiments.

The IMBLMS is essentially a compactly packaged unit built in modular form to allow simple exchange of measuring equipment. This concept lends versatility to the system by enabling the simple replacement of old techniques with new ones, and the substitution of gross observations with finer measurements and discriminations in implicated investigative areas. It also permits rapid and less expensive integration of approved medical in-flight experiments and optimization of equipment commonality and crew tasks.

Non-invasive instrumentation and microtechniques are emphasized in order to reduce the requirements on the operator and the discomfort to the subject. The total system consists of physiological, biochemical, behavioral, microbiological and data management components. The desired measurements capability of IMBLMS is shown in Table I.

Significant crew participation in investigative activities will be required involving such measurements as alveolar-arterial O_2 gradient, regional blood flow, venous pressure, cardiac output, onboard hematological measurements, breath-by-breath measurement of O_2 consumption and CO_2 production, onboard bone densitometry, microbiological and immunological studies and a battery of clinical laboratory biochemical determinations together with advanced data management capability. Activities will be planned eventually, with a view to affording astronauts adequate time for direct participation in experiment protocols.

Flight availability of IMBLMS is expected by 1972. Until this time individual experiments will be integrated with each other as well as possible. After the IMBLMS become available selected modular components will be included on flights which do not call for utilization of the entire system.

TABLE I

MEDICAL/BEHAVIORAL MEASUREMENT CAPABILITY OF INTEGRATED MEDICAL AND BEHAVIORAL LABORATORY MEASUREMENTS SYSTEM

I. NEUROLOGICAL

- Clinical Evaluation (to include reflexes and sensory and motor pathways)
- Agravic Perception of Personal and Extra-Personal Space (Minimum restraint device)
- Ocular Counter-Rolling
- Oculogyral Illusion
- Visual Task with Head Rotation
- Electronystagmogram
- Angular Acceleration Threshold

(Ocular Counter-Rolling through Angular Acceleration Threshold: To be done with litter-chair)

- EEG

II. CARDIOVASCULAR

- Clinical Evaluation
- ECG (Frank Lead System)
- Phonocardiogram
- Cardiac Output - (By impedance if technique verified; by indicator-dilution if necessary)
- Arterial Blood Pressure
- Venous Pressure - Peripheral
- Blood Volume and Fluid Compartments - See Hematology and Metabolism
- Regional Blood Flow - Limb (or Digit) (Distribution of Blood Volume)
- Venous Compliance
- Arteriolar Reactivity

(Regional Blood Flow through Arteriolar Reactivity: Limb Plethysmography)

- Arterial Pulse Contour
- In-Flight Exercise
- LBNP
- Elastic Leotards

PROVIDE FOR INSTALLATION IF REQUIRED:

- Ballistocardiogram
- Carotid Body Stimulation
- Thoracic Blood Flow
- Venous Pressure - Central (By Catheter if Necessary)

III. RESPIRATORY

- Clinical Evaluation
- Respiratory Rate
- Lung Volumes Including Residual Volume (For total lung capacity, and mixing efficiency)
- Pressure, Flow, and Volume (Simultaneously) (+Airway Resistance)
- Compliance - Lung or Total (Lung if can)
- Distribution of Blood Flow and Gas in Lungs

Includes:
- Capillary Blood O_2, CO_2, and pH
- Breath by Breath O_2 Consumption and CO_2 Production
- O_2 Consumption - With Measured Exercise
- Alveolar to Arterial Gradient Breathing Air and 100% Oxygen

- Diffusion Capacity (if suitable technique) (Look into O_2^{18} method - Dr. Richard W. Hyde, U. of Pennsylvania, Dept. of Physiology)

IV. METABOLISM AND NUTRITION

- Clinical Evaluation
- Energy Metabolism (Continuous O_2 and CO_2 Analysis with Breath by Breath Sensitivity) with Various Levels of Activity
- Oral Temperature
- Skin Temperature
- Caloric Intake
- Body Mass In-Flight (Thornton Technique - GFE)†
- [Lean Body Mass Pre- and Post-Flight] - (Not a Part of IMBLMS)
- Muscle Size and Strength
- Balance Studies
  - Fluid, including Sweat
  - Nitrogen (See Area IX)
  - Mineral (See Area IX)
  - Electrolyte (See Area IX)

Provide for:
- Accurate Urine Volume Measurement
- Accurate Wet Weight of Feces
- Return of Total Dry Stool
- Accurate Fluid Intake Measurement
- Return of all Food Packages Marked by Date Time and Individual
- Sweat Measurement and Sample Return

- Total Body Water (Breatholator or Deuterium)
- * Clinical Laboratory Evaluations - See List Under Area IX

PROVIDE FOR INSTALLATION IF REQUIRED:

- EMG
- Bone Densitometry - Isotope Technique
- Gastric Pressure and pH (Endoradiosonde)
- Plasma Volume On-Board
- Mineral Metabolism by Isotopic Techniques

V. ENDOCRINOLOGY

- Clinical Evaluation
- * Clinical Laboratory Evaluations - See List

VI. HEMATOLOGY

- Clinical Evaluation
- Rumple Leede
- Blood Volume and Fluid Compartment
  - Plasma Volume - RHISA
  - RBC Mass - DFP^{32} or Cr^{51}
  - Total Body Water
- RBC Survival - DFP^{32}
- Clinical Laboratory Evaluations - See List

† Government Furnished Equipment

VII. MICROBIOLOGY AND IMMUNOLOGY

- Clinical Evaluation
- Body Microflora (Bacterial, Viral, and Fungal)
- Environmental Culturing (Bacterial, Viral, and Fungal)
- Clinical Laboratory Evaluations - See List

VIII. BEHAVIORAL EFFECTS

- Clinical Evaluation
- Sensory Test Battery (See Also Neurology)
- Perceptual Evaluation (If validity of Tests Established)
- Higher Thought Processes
- Memory - Short and Long Term
- Vigilance (By measurement of operational tasks)
- Learned Activity (Tracking and Reaction Time)
- Recording of Crew Intercommunication with Automatic Erase in 15 Minutes if not Sampled
- Time and Motion Study

IX. CLINICAL LABORATORY EVALUATIONS

- Creatine and Creatinine - Urinary
- Urinary and Fecal: N, Ca, P, Na, K, Cl, and Mg
- Mucoproteins - Urinary (Pi)*
- Pyrophosphates - Urinary (Pi)
- Hydroxyprolines - Urinary (probably Pi)
- Total Amino Acids - Urinary (Pi)
- Urinary: Osmolality, Color, Sp Gr, pH, Glucose, Protein, Bile, Blood, and Microscopic (i.e., Routine Urinalysis - Inflight)
- Plasma Volume (probably P&P)**
- Electrolytes - Serum
- Total Protein - Plasma
- Glucose - Blood (Inflight)
- Ca and PO_4 - Serum (probably Pi)
- Bilirubin - Serum
- Cholesterol - Serum (probably Pi)
- BUN (probably Pi)
- Uric Acid - Blood (Pi)
- Alkaline Phosphatase - Serum (probably Pi)
- pH, pO_2, and pCO_2 - Blood
- Bicarbonate - Blood
- CPK (Creatine Phosphokinase - Serum (Pi)
- LDH and LDH Isoenzymes - Serum (On-board if have electrophoresis)
- SGOT - Serum
- SGPT - Serum
- Aldosterone - Urine (Pi)
- ADH - Urinary and Serum (Pi)
- ACTH - Blood (Pi)
- Serum Free Thyroxin (T_4 - Serum) (If in-flight, will require thin layer chromatography)
- TBPA (Probably Pi)
- 17-hydroxycorticosteroids - Urine and blood (Pi)
- 17-ketosteroids - Urine (Pi)
- VMA - Urine (Probably Pi)
- Metanephrines - Urine (Pi)
- Catechols - Urine (Pi)
- Histamine - Blood and Urine (Pi)
- 5 Hydroxy indolacetic acid - Urinary (Probably Pi)
- Blood Cell Morphology (RBC, WBC, and Diff - Smear will suffice for platelets)
- Reticulocyte Count
- Hematocrit
- Hemoglobin
- RBC Fragility (Osmotic)
- RBC Mass and Survival
- Bleeding Time
- Clotting Time
- Prothrombin Consumption
- Clot Retraction
- Lymphocyte Karotyping (Probably Pi)
- WBC Mobilization (Rebuck Technique)
- Immunoglobulins and Fibrinogen
- Transferins
- Hemoglobin
- Methemoglobin

(Immunoglobulins and Fibrinogen through Methemoglobin: onboard if have electrophoresis)

- RBC Enzyme Studies (Pi) (ref. Governing Protocol M110)
- Complement Titration
- Antibody Titration

PROVIDE FOR INCLUSIONS IF REQUIRED:

- Sulfate - Urinary
- TSH (Pi)
- Growth Hormone (Pi)
- Thyroid Bound Globulin (T_3) (Pi)
- Parathyroid Hormone (Radio-immune Technique - Serum) (Pi)
- Parathyroid Hormone - Urinary (Nelson Technique) (Pi)
- Calcitonin - Serum (Pi)
- Insulin Assay (Pi)
- Glucagon Assay (Pi)
- Serotonin (5 HIAA) - Blood (Pi)
- Platelet Adhesiveness
- Fibrinolytic Activity
- Blood Rheology
- Blood Lipids

* Pi - Post-flight evaluation of in-flight samples

** p&p - pre- and post flight

STRATEGIES AND TACTICS

BASIC ISSUES

The problem of "space rating man" entails two basic questions:

1. What information do we need in order to plan confidently and carry-out manned space flights of long duration? and
2. What are the best strategies and tactics for obtaining this information?

INFORMATION NEEDED

1. Specification of the Space Flight Environment

The inflight astronaut environment includes internal space cabin parameters as well as natural features* of outer space. The medical implications resulting from the principal elements of the total environment are discussed in Parts II, III and IV of this document. Some of these elements are well defined, others (such as radiation, magnetic fields and altered periodicities) require further research and analysis. Still others can occupy any of a range of values, because they are part of the man-made environment within the space capsule, and thus subject to direct modification.

Sufficient knowledge presently exists about man to understand that little can be done to increase his physiological

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*Natural Environment and Physical Standards from Manned Flight Programs, OMSF, SE 015-001-1B, January 1969.

tolerance to in-flight stressors; other than to improve selection methods and training procedures. The approach is not to recast man as an altered animal system, but rather to provide for him an environment compatible with life as we know it, a reasonably comfortable place in which to work, and meaningful productive tasks to accomplish. The crew must be furnished with a superb unit for habitation and with all the ancillary goods and facilities necessary to keep them healthy, happy and productive.

2. Delineation of the Effects of These Environmental Parameters or Man's Health and Performance

Ideally, one should be able to specify the effects of a single variable acting alone and in combination with other variables.* In practice, one deals with complex combinations of variables, both on the environmental and the physiological-behavioral side, which act collectively, affect individually more than one area of body function and are difficult to evaluate singly. A primary problem in space-rating man is that of resolving this tangle of variables so that meaningful functional relationships can be established and design criteria and procedures can be deduced from principles. Evoked responses must also be studied in terms of the various systems of physiological and psychological function that comprise the whole man. Investigative aims are idenfitied in the section "Overall Positions and Objectives".

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*Compedium of Human Responses to the Aerospace Environment, Vol, I, II, III and IV, NASA CR-1205, November 1968.

3. <u>Specification of Operational Options in the Planning and Execution of Space Missions</u>

These options fall into the following categories:

a. Mission organization (including contingency plans and mission rules)

b. Environmental engineering

c. Crew selection and training

d. In-flight maintenance and prophylaxis

e. In-flight monitoring of crew and environment

f. Emergency procedures and remidial measures.

One must determine the implications of available knowledge in areas 1 and 2 above on the options specified in 3. That is, as information about the space environment and its effects on man accumulates, the workable combinations of functional options are determined. When alternative solutions to a given man-in-space problem are feasible, the simplest and least expensive will generally be selected. However, some solutions may be convenient temporarily, but later must yield to other, more permanent, solutions. For example, in the present state of space travel, only individuals who can tolerate an unusual range of stresses are being selected for space crews. It is anticipated that since space flight will eventually become relatively common, this crew selection will become obsolete with the advent of more difficult solutions involving mission organization and environmental engineering; thus, selection criteria will be liberalized, permitting a wider range of individuals to travel in space.

HOW TO ACQUIRE THE NECESSARY INFORMATION

The program strategy to accomplish the objective of space rating man consists of essential ground-based research and technology activities, and the development and conduct of related flight experiments.

Ground-based Research

A well defined ground-based research program is absolutely essential to the success of the overall biomedical effort. This ground-based program must enbody two essential elements. The first is the research required to resolve actual problems which have been detected as a result of our experience in space flight. The second is the research required to answer potential or anticipated problems which might occur on extended missions.

In-flight Studies

Many space flight stressors can be simulated on the ground but the actual flight situation cannot be duplicated in the laboratory. Consequently, an in-flight biomedical program consitutes the only approach that can confidently confirm the effects of prolonged space flight on man, the time courses of these effects, the mechanisms by which these effects are mediated, the means of predicting their onset and severity, and the appropriate preventive or remedial techniques to cope with them.

The flight experiment approaches for the biomedical and behavioral program include:

1. Astronaut monitoring and selected flight experiments on all manned flights;

2. Specific manned flights which are designed to permit in-depth measurements and experiments on and with man and concurrently on animals, and auxiliary cytological, histochemical and biochemical research. Supportive animal, and/or biological experiments, however, should be limited to the ground-based portion and remain as a stand-by capability to supplement in-flight medical research only if a definite need exists or arises.

The general philosophy of the in-flight Biomedical/ Behaviroral program is to provide:

1. In-depth investigations of problems one expects or knows about; and
2. Human systems monitoring across the entire spectrum on an attempt to identify problems before they become manifest or critical.

In pursuing this philosophy basic principles apply which relate clearly to flight program planning.

1. The key variable in the evaluation of man in space is duration of flight. Thus, medical/behavioral measurement of flight crew members will be required more frequently during the extended portion of an incremental mission than earlier in that mission, although they will in general be qualitatively the same.
2. It is important to obtain a great a redundancy of pertinent measurements of individual crew members

as is practicable in any given flight configuration to establish statistical validity.

3. A major practical aim of this effort is to utilize these observations and to be prepared with appropriate preventive or remedial techniques. For example, in the cardiovascular area, such techniques as lower body negative pressure, special exercises and other conditioning methods for maintaining the circulatory system in a satisfactory condition during future long-duration missions are under investigation. This concept also includes the evaluation of the long term effects of zero-G to determine the desirability or need for artificial gravity (i.e., to conduct the observations required in order to make the so-called "g decision").

Alternate Flight Strategies

Certification of man's capability to extend his orbital stay time has in the past been predicated on the assumption that a previous stay time which resulted in no unacceptable physiologic or performance decrement could safely be doubled for a subsequent mission. This has been done, in the main, on the basis of pre- and postflight measurements and in-flight monitoring of a few selected physiological parameters. This philosophy has been successful for mission durations to 14 days. In the course of these missions, significant physiological changes have been observed (e.g., red cell mass deficit, bone demineralization, cardiovascular deconditioning, micro-flora changes, and fluid recompartmentalization) which require further understanding before predictions can be safely made regarding man's capabilities for longer exposures. Controlled in-flight experimental data must now be obtained to elucidate the mechanisms responsible for these changes.

It will be necessary that the experimental protocols designed to obtain these data be successfully implemented in a 28 day mission before man is qualified for longer missions. However, the biological defensibility of the current practice of two-fold extension in flight duration decreases with increasing exposure increments. Consequently, alternate approaches are presently under consideration. These include:

1. Extension of crew exposure in increments of 30 days. This approach increases the margin of safety and appears to be more acceptable to the inherently conservative scientific-medical community. Continuous monitoring of the health status of the crew will be the basis for judgment on day-to-day continuation of the mission on the principle that all earth-orbital flights can be terminated at will.
2. A flight exposure medically open-ended. Two possibilities are available. The first entails an 8-man crew with replacement of 2 members at 90 days,* 2 at 120 days, 2 at 150 days, and removal of all at

*Assumes successful completion of the 30 and 60 day AAP missions.

180 days. Continuation of the ongoing mission will depend on the physiological status assessment of the returned astronauts. The second requires that a 3 or 4 man crew is placed in orbit and is maintained there under close medical surveillance (both physiological and psychological); the flight is terminated on the occurrence of pre-established unacceptable responses. A highly reliable indicator of astronaut ability to tolerate re-entry stresses and readapt to the terrestrial environment, is mandatory for the success of this approach.

3. Flight exposures of duration equal to the time constants of important periodic physiological events. It is well established that many physiological functions reflect an inherent rhythmicity or periodicily with regard to time. Basic drives such as sex, hunger, and thirst, produce an increasing awareness of a need for statisfaction as a function of time. Following the gratification of a basic drive, the process of increasing need begins again, terminating in a repetiton of the gratification act. These are simple examples of a more complex phenomenon of cyclical changes that occur in the body with the passage of time. Many examples may be drawn from the phenomena of cell and tissue development, growth, multiplication, and replacement. Some representative biological cyclical events with their

respective time periods, listed according to the phenomenon starting with 4 days and ending with 2048 days or more, are shown in Figure 1. Sleep cycles are periodic and occur within a time period of hours, as do certain changes in the gastrointestinal epithelium. The lymphocyte changes appear to occur at 2- to 3-day intervals. On the basis of Figure 1, if one were to double a 32-day flight duration to 64 days, planned experimental observations on the metabolic turnover of calcium and phosphorous in the bones would be obscured by the stressful activities that are associated with flight termination and recovery. It is known that red blood cells have a life expectancy of approximately 120 days. If one were to continue to the policy of doubling flight durations, a 128-day mission would be scheduled for termination during a period in which critical observations would be disrupted. An example of how flight durations may be selected to satisfy at least one specific experimental protocol is given in Figure 2. The example is the study of the mineralization and demineralization of the bones as determined by precise measurements of calcium phophorous, and other biochemical constituents of the plasma and urine. On the left, the cross-hatched area represents a period of undetermined length in which it can be presumed that the stresses common to prelaunch, launch, and station setup would negate useful research activities for a certain number of hours or days. This period is followed by a period during which useful measurements and experimentation may be accomplished. The latter period must encompass sufficient time to complete a series of replicated experiments to gather adequate data for statistical evaluation.

THE NEED FOR A SPACE STATION

Three highly attractive features of the space environment suggest that the exploitation of extended operations in Earth orbit can result in scientific and economic returns. These are:

1. Weightlessness - which permits a new insight into physical, chemical and biological processes through experiments not possible in the gravity field of the terrestrial environment.
2. Absence of atmosphere - which permits astronomical observations throughout the electromagnetic spectrum. This can also help in the search for extraterrestrial life by enhancing remote studies of the planets.
3. Comprehensive overview - which permits observation of extensive areas of the earth's surface desirable for communications, weather forecast, and resources surveys.

The exploitation of such features can benefit from the presence of man both as a scientist-researcher and as a technician-operator. In addition, exploration of the planets appears inevitable and man can contribute significantly if placed at the point of data collection. Therefore, in this respect man's qualification for long duration space flight is a prerequisite for achieving all other manned space flight objectives. Two critical questions can be identified and answered by an earth-orbital biomedical and behavioral program:

1. Can man perform satisfactorily during prolonged term exposure to space flight conditions?
2. What are the system concepts and operational techniques necessary to preserve man's proficiency in space and enhance his effectiveness?

It would appear that the only realistic way to obtain systematically the scientific and operational information required by the proposed medical program, is in the use of an Earth-orbital space station. A life sciences laboratory aboard the space station will:

1. End present opportunistic approaches to research scheduling;
2. Eliminate competition for the astronauts' time and effort which presently results in demanding time-lines;

3. Permit greater research flexibility and experiment protocol freedom than is presently available.
4. Allow task and equipment integration in a manner not presently possible.
5. Provide the large crew size required to validate statistically medical results.
6. Provide extended vehicle life-time capability.

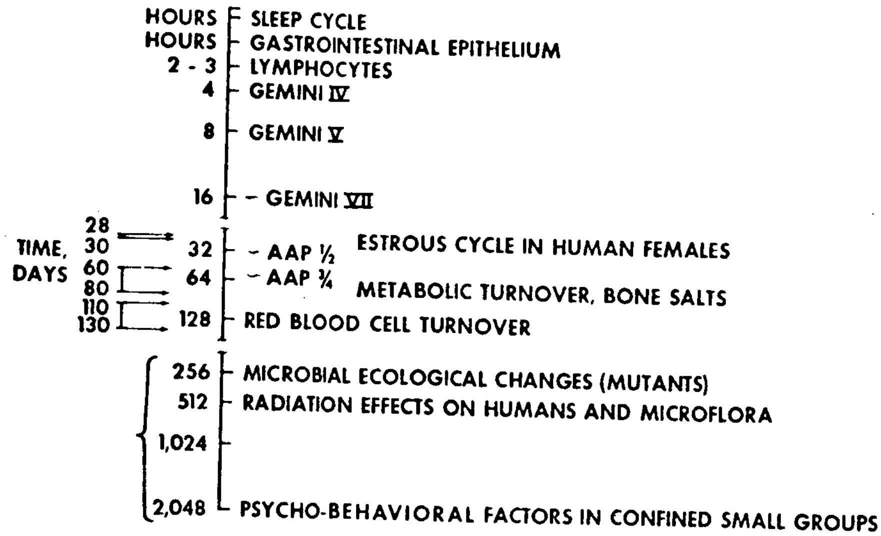


FIGURE 1 - TIME LINE FOR EXPERIMENT PLANNING.

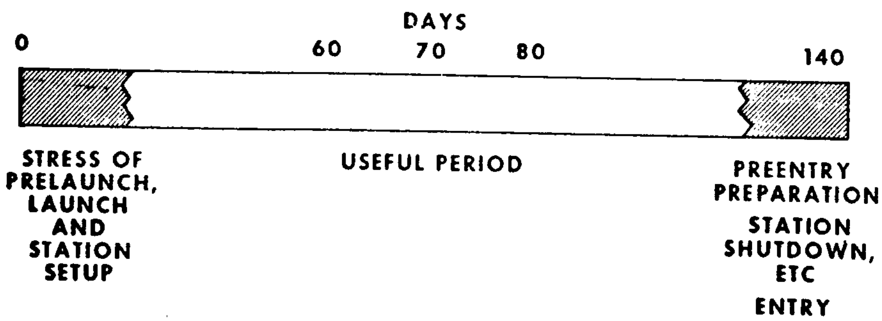


FIGURE 2 - EXPERIMENTALLY USEFUL PERIOD FOR A 140-DAY MISSION.

LAUNCH-MAN SEQUENCING FOR EXTENDED MISSIONS

In a comprehensive analysis of the effects of the space environment upon astronauts as their length of exposure in orbit varies it is necessary to determine the man-mission resupply schedules possible under various constraints. Some of these constraints are dictated by the psychological and physiological analyses, such as the different durations of exposure periods to be considered, the number of exposure periods and their required sequencing. Other constraints are dictated by the physical limitations of the mission such as the number of astroanuts in the vehicle and the minimum and maximum resupply intervals. Still others are cost and safety factors such as the number of astronauts to be exchanged at any resupply, the total number of launch vehicles, and the resupply lag immediately preceding the termination of the mission. Practicality would require that as much as possible be accomplished for a fixed set of constraints; thus mission duration is to be maximized which will in turn tend to maximize the number of astronauts exposed giving larger statistical samples for analysis.

A specific set of constraints will be assumed for which all mission schedule types will then be determined and those chosen which maximize mission duration. These constraints are as follows:

A. Fixed Constraints

1. There are three astronauts in orbit at all times,
2. the minimum lag between resupply launches is 30 days,
3. the maximum lag between resupply launches is 90 days,
4. two launch vehicles are required for the initial launch,
5. one launch vehicle is required for each resupply,
6. an initial sequencing is required of a 30 day man being returned before any man has been exposed for 60 days, a 60 day man being returned before any man has been exposed for 90 days and a 90 day man being returned before any men have been exposed for greater than 90 days,
7. the mission is terminated at the end of the longest exposure period,
8. the bounds on the number of astronaut periods of exposure are

	Number of periods	
Length of period in days	Minimum	Maximum
30	1	3
60	1	3
90	1	3
120		3
150	1	3
180		3
210	0	3
240	0	3
270	0	3
300	0	3
330	1	3
360		2

B. Varying Constraints or Desired Properties

1. The longest exposure period required is either 330 days or 360 days in length,
2. the limit (m) on the number of astronauts that can be exchanged at any resupply is either 1, 2 or 3,
3. the limit (r) on the resupply lag immediately preceding the termination of the mission is either 30, 60 or 90 days,
4. the number (ℓ) of launch vehicles.

CLASSIFICATION BY INITIAL SEGMENTS

For simplicity, due to the minimum lag constraint, a 30-day period will be called a unit period (or a unit) and visually, a 30-day period will be represented as a block 1 unit in length, a 60-day period as a block 2 units in length, a $30 \cdot k$ day period as a block k units in length.

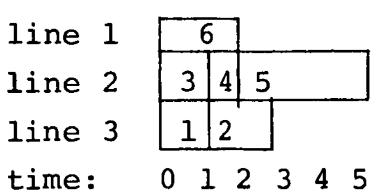
To facilitate analysis, the set of all missions will be partitioned into a sufficiently small collection of distinct classes each characterized by its "initial segment." The initial segments are arrived at and defined by using the following of the fixed constraints

i) there are 3 astronauts in orbit at all times (A.1),

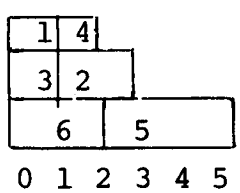
ii) no more than 3 each of length 1, length 2 and length 3 blocks can be used (A.8), and

iii) the precedence relations that at least one length 1 block must end before any block exceeds length 1, at least one length 2 block must end before any block exceeds length 2 and at least one length 3 block must end before any block exceeds length 3 (A.6).

Indeed, condition iii) implies that no longer block can start before the first 1 unit block, the first 2 unit block, or the first 3 unit block starts, respectively. Hence, an <u>initial segment</u> will be defined to be a segment from the beginning of a mission to and including the first 3 unit block with all three astronaut positions (condition i) filled by 1 or 2 unit blocks to at least the beginning of the first 3 unit block. This precludes any block 3 units or longer from starting too soon. Two segments are said to be <u>symmetric</u> if one can be obtained from the other by rearranging the blocks from line to line while keeping each block in its own fixed time interval. This symmetry is illustrated by the following example:



(a)



(b)

The segment (a) is symmetric to the segment (b) and vice versa. Under the three constraints (i) - (iii) there are eleven and only eleven initial segments within symmetry. Therefore any mission satisfying these constraints must have a beginning symmetric to one and only one of the eleven segments in

Figure 1. Note that the end of a block is the termination of that man's stay in orbit; if a block is followed by another block, then there is an exchange of astronauts. Thus the end of a block requires a launch; the launches required by each initial segment are shown in Figure 1.

INITIAL SEGMENT CAPABILITY ANALYSIS

An initial segment is capable of a desired property or properties if a mission profile can be constructed having the desired property or properties and having a beginning symmetric to the initial segment. The eleven initial segments have been analyzed with regard to the properties of B. (i.e., the constraints of B.). The more "capable" initial segments are numbers 1, 2 and 9. That is to say, that for any given desired property set (e.g., a mission profile is wanted so that 1) no more than 2 astronauts are exchanged at any one time, 2) the longest exposure period for an astronaut is 330 days (11 units), 3) there is a launch 60 days (2 units) prior to the end of the mission and 4) 8 launch vehicles are to be used) a mission profile can be constructed using one of these three initial segments as a beginning, satisfying the desired property set and having at least the duration attainable by using any of the eleven initial segments. The capabilities of initial segments 1, 2 and 9 are summarized in Figure 2. To find the initial segment(s) capable of the example property set above, look for the symbol under the 8 launch vehicle column and initial segments 1 or 2 since the exchange limit is m=2; there is one entry having a duration of 15 units (450 days) using initial segment 2. Then using initial segment 2 from Figure 1, a mission profile can be constructed exhibiting the desired properties; such a profile is shown in Figure 3 (initial segment number 2 with n=13; n is the number of men used for the particular mission profile). This profile shows launches at 0, 30, 60, 120, 210, 300 and 390 days from the start of the mission (each unit is 30 days); 2 men are exchanged at all but 2 launches (those two being at unit 7 (210 days) and 13 (390 days)) where one man is exchanged. Other example mission profiles are shown in Figure 3. The shaded portions are fixed by the initial segment and the desired properties; the remainder has been filled in to obtain a maximum number of men exposed under the fixed constraints of A.

Constraint sets other than those analyzed herein can be analyzed similarly. Preliminary analyses have been done on several other such constraint sets varying constraints A.6, A.8 and B.1. A specific such variation is where A.6 becomes

A.6'. an initial sequencing is required of two 30 day men being returned before any man has been exposed for 60 days, two 60 day men being returned before any man has been exposed for 120 days and two 120 day men being returned before any man has been exposed for greater than 120 days;

A.8 becomes

A.8'. the bounds on the number of astronaut periods of exposure are

		Number of periods	
		Minimum	Maximum
Length of period in days	30	2	3
	60	2	3
	90	0	3
	120	2	3
	150	0	3
	180	2	3

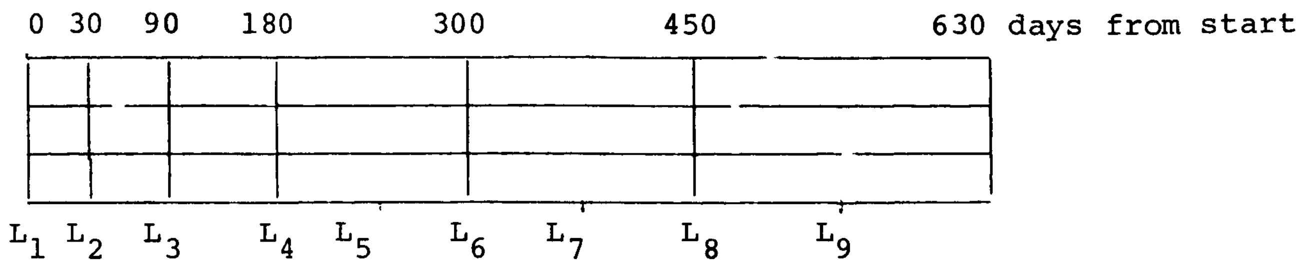
and B.1 becomes

B.1'. The longest exposure period required is 180 days in length.

Another constraint set analyzed is where constraint A.6 becomes

A.6". an initial sequencing is required of an X day man being returned and having 10 days for examination before any man has been exposed for greater than X days, for X = 30, 60, 90, 120, 150.

and constraints A.8 and B.1 become A.8' and B.1', respectively. For this set of constraints there is essentially one and only one mission profile that being



where L_i is the i^{th} launch; this requires at least 10 launch vehicles.

An expanded version of the analysis and the mathematical basis are contained in a technical memorandum*.

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*Launch-Man Sequencing for Extended Mission Effectiveness Study, <u>Bellcomm Technical Memorandum</u>, TM-68-1033-6, L. D. Nelson, December 16, 1968.

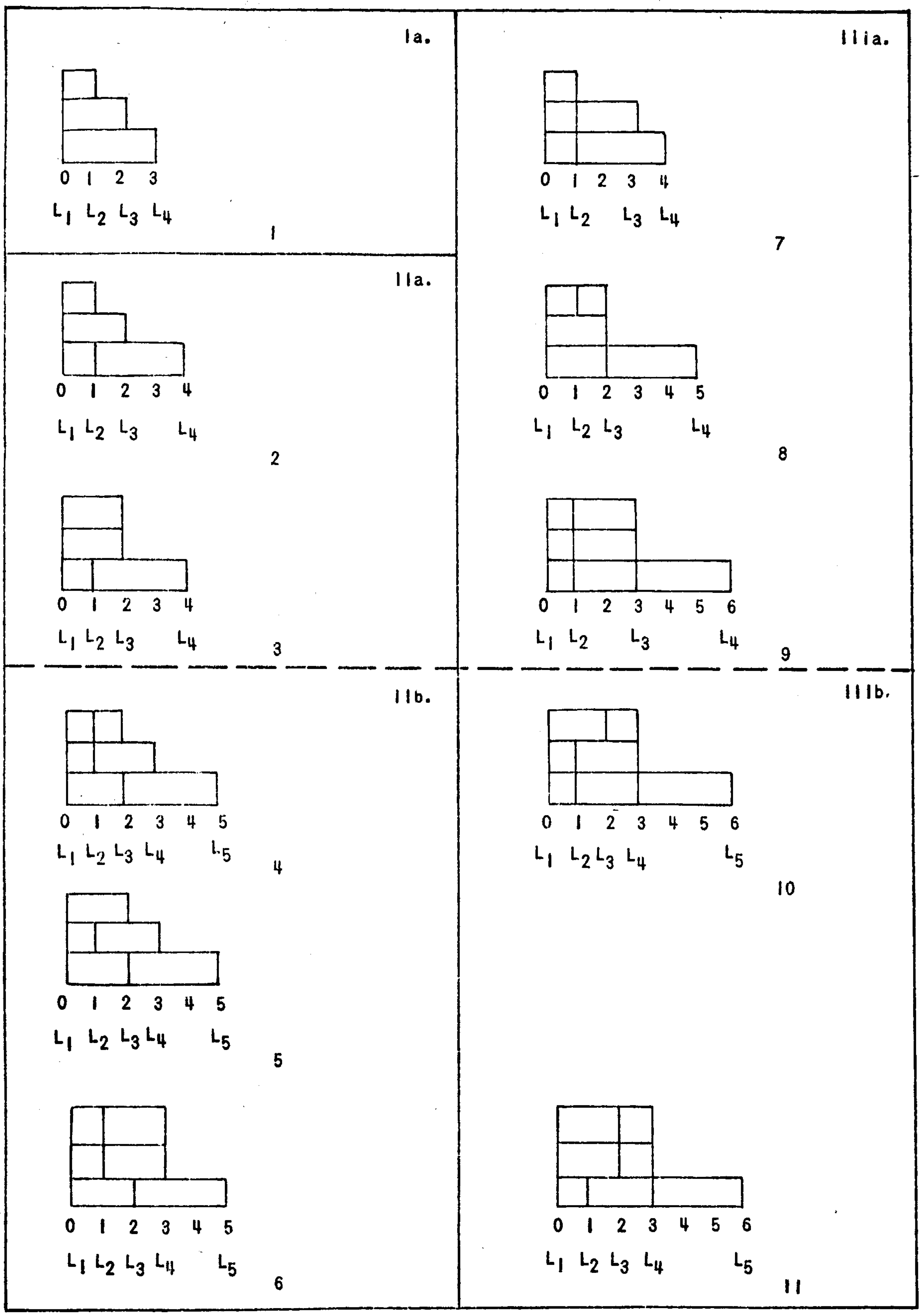
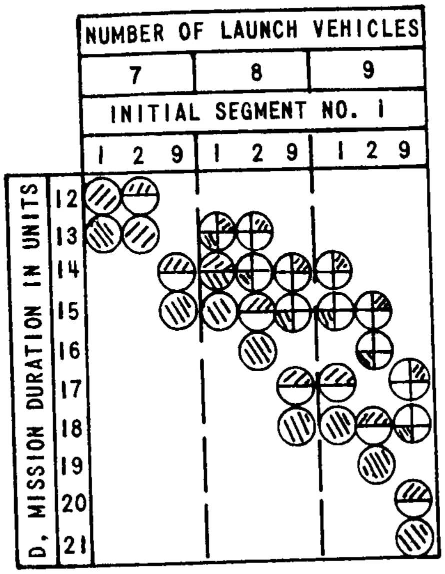


FIGURE I. - THE SET OF POSSIBLE INITIAL SEGMENTS FOR 3-MAN, MAXIMUM OF 3 EXPOSURE PERIODS OF THE SAME LENGTH ONE-TWO-THREE LONGER PERIOD REQUIRED SEQUENCING. THEY ARE CATEGORIZED INTO:

I. - INITIAL SEGMENTS REQUIRING A MAXIMUM OF 1-MAN EXCHANGE,
II. - INITIAL SEGMENTS REQUIRING A MAXIMUM OF 2-MAN EXCHANGE,
III. - INITIAL SEGMENTS REQUIRING A MAXIMUM OF 3-MAN EXCHANGE.

FURTHER, THE REQUIRED LAUNCHES ARE NOTED BELOW EACH SEGMENT BY L_i AND THE SEGMENTS ARE SUBDIVIDED INTO THOSE REQUIRING a) 4 AND b) 5 LAUNCHES. EVERY UNIT PERIOD IS A 30 DAY PERIOD.



LEGEND:

330 DAYS	360 DAYS	←LONGEST EXPOSURE PERIOD P (k UNITS LONG)	
		90 DAY TERMINAL LAUNCH LAG MINIMUM	r = 3
		60 DAY TERMINAL LAUNCH LAG MINIMUM	r = 2
		30 DAY TERMINAL LAUNCH LAG MINIMUM	r = 1

ASTRONAUT EXCHANGE LIMIT IS	THEN CONSIDER INITIAL SEGMENTS NO'S
m = 1	i=1
m = 2	i=1,2
m = 3	i=1,2,9

FIGURE 2 - MAXIMUM DURATION CAPABILITY CHART FOR INITIAL SEGMENTS. THIS CHART EXPRESSES THE CAPABILITIES OF THOSE INITIAL SEGMENTS HAVING THE MAXIMUM DURATION PROPERTY FOR EACH VALID FIXED SET OF PROPERTIES a) 7,8, OR 9 LAUNCH VEHICLES, b) 330 OR 360 DAY LONGEST EXPOSURE PERIOD, c) 30,60, OR 90 DAY TERMINAL LAUNCH LAG AND d) 1,2, OR 3 ASTRONAUT EXCHANGE LIMIT.

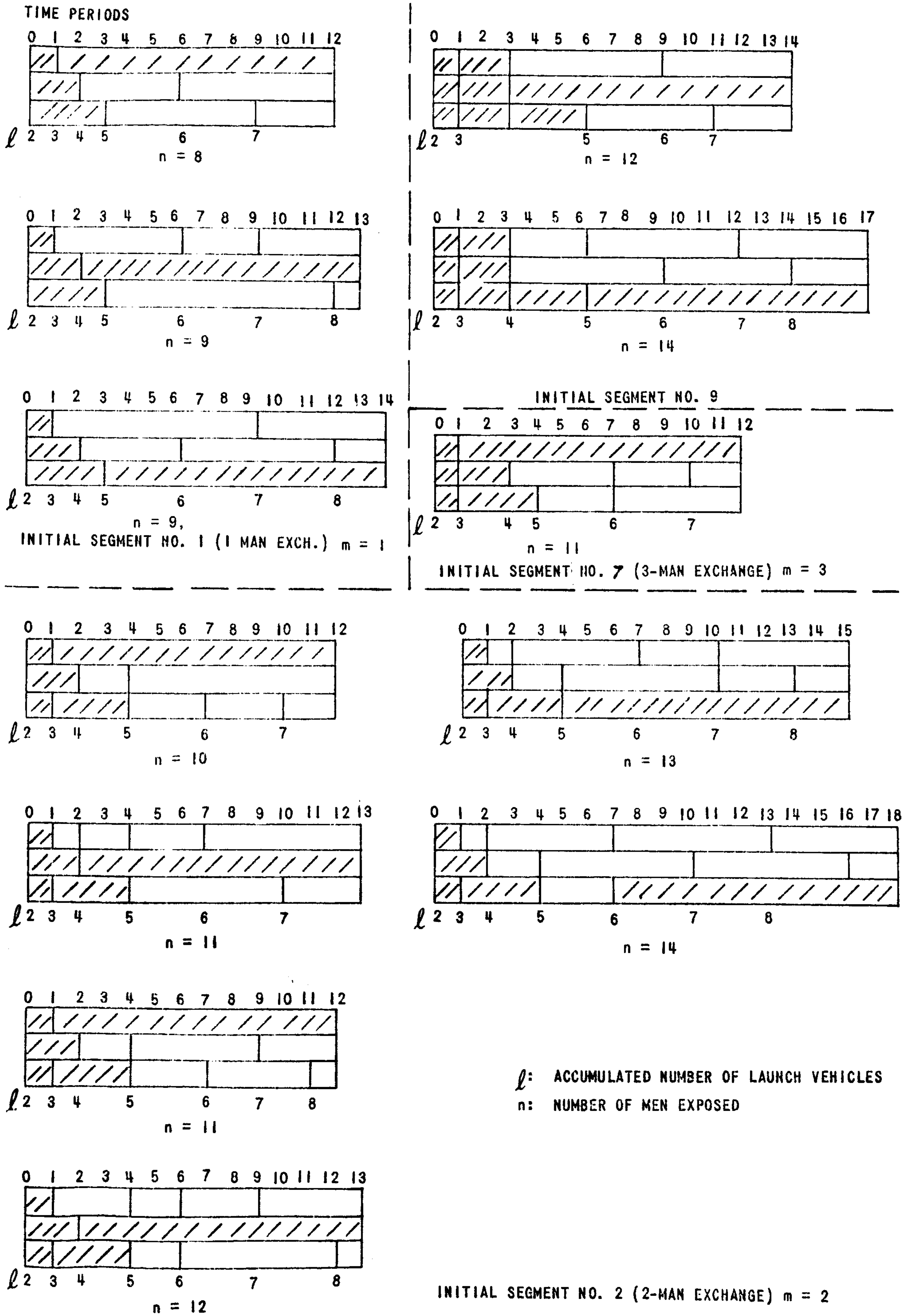


FIGURE 3 - EXTENDED MISSION EXAMPLES